Wearable Computers and Spatial Cognition

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

College of Computing
Georgia Institute of Technology
August 20, 2004

Wearable Computers and Spatial Cognition

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Date Approved: August 20, 2004

ACKNOWLEDGEMENTS

My research has examined how wearable computers can help people understand the environments through which they travel. My PhD has also been quite a journey, and I am grateful for the many people who have helped me find my way. Although I will inevitably neglect to mention some names, I hope it will be understood that this is an absence of mind, not an absence of heart.

I would like to thank Dr. Bill Ribarsky and Dr. Larry Hodges for bringing me into their research groups, extending great opportunities, and advising me throughout my time at Georgia Tech. I also thank the other members of my committee: Dr. Blair MacIntyre, Dr. Jeff Pierce, Dr. Thad Starner, and Dr. Bruce Walker for their help and guidance.

I am also grateful to Dr. Chris Shaw for the advice and the many discussions that he shared with me. Dr. Gregory Abowd and Dr. Jim Foley also helped deepen my understanding and appreciation of the field of human-computer interaction.

Every PhD student is mentored by another more senior student. Zach Wartell was that mentor for me. I could always turn to him for help. I learned a great deal about virtual environments, stereoscopic displays, and many other topics from him.

I also thank the current and past members of the Virtual Environments group and the Virtual Worlds Lab: David Prince, Chad Wingrave, Cathy Zanbaka, Benga Omoteso, Tazama St. Julien, Don Allison, Jeff Wilson, Doug Bowman, Jarell Pair, and many others. Other graduate students at Georgia Tech have helped me by sharing their ideas, advice, and friendship: Khai Truong, Rob Melby, Dan Ashbrook, and Ari Lamstein.

I am greatly indebted to Dr. John Allensworth, his geography classes at Georgia State University, and the many other participants of my user studies.

Before I came to Georgia Tech, two professors helped reveal new paths and ideas to me. At the University of Alabama in Huntsville, Dr. Tim Newman, guided me through my Masters degree, and always had words of encouragement. At Caltech, Dr. Jan van de Sneupschut gave an eye opening view of computing as a science to a wide-eyed, young undergraduate student.

I give my love and thanks to my parents: Richard and Judy Krum. They gave me curiosity and many opportunities to explore science, computers, and culture. I also give my love to my brothers: Stephen and Patrick, and my sister Megan.

There is a special place in my life and in my heart for Linh Lu. I am especially indebted to her for all the patience and support that she has given me. I could not have completed this without her. My love, my hopes, and my dreams are with her.

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SUMMARY

Human beings often live, work, and travel through complex outdoor environments. Some examples of these environments include: a university campus, a shopping mall, an office park, a suburb, or an entire city. These environments can have intricate networks of roads, paths, overpasses, and tunnels. Other features, such as buildings, hills, and trees, add further complexity and can obscure other parts of the environment. It can be a challenge for individuals to understand and navigate these surroundings. The daily commute can be an intricate journey through a large freeway system, small streets, and around traffic. A trip to a shopping mall can be a bewildering experience in a maze of stores.

For individuals who are visiting a new area or have recently moved to the area, it can be especially difficult to understand the layout of the environment, locate particular buildings and services, and find friends, family, and co-workers. There are also particular careers that may frequently place individuals in unfamiliar locations. For example, military or law enforcement personnel may travel to a new area of operations and need to quickly learn the lay of the land in order to efficiently patrol and coordinate activity with others.

In this dissertation, I describe a research program that investigated the use of wearable computers to help individuals perceive, understand, and learn the layout of the surrounding environment. That is, employing wearable computers as a platform for a spatial cognition or spatial learning aid.

This research program was guided by a relationship mediation model of wearable computing. The relationship mediation model identifies and describes the user relationships in which a wearable computer can participate and mediate. Some of these relationships include user to environment, user to wearable computer, and user to other individuals. Wearable computer applications, such as a spatial cognition aid, can be described by identifying the particular relationships involved and detailing how the wearable participates. There are three vital relationships involved in a spatial cognition aid: a wearable computer to environment relationship, a user to wearable computer relationship, and a user to environment relationship which is mediated by the wearable computer. The research

program described in this dissertation consists of three components which correspond to those three aforementioned relationships.

The first component is an infrastructure that allows wearable computers to gather location based environmental information, which is important for the wearable computer to environment relationship. This infrastructure consists of three components: client applications on mobile or wearable computers, location servers, and data servers. Location servers maintain a location registry of clients and data servers in a particular region. Clients can communicate an area of interest to a particular location server. That location server responds with a list of data servers and other clients for that area of interest. The client application can then access the data servers that provide information of interest to the user, perhaps weather reports, traffic conditions, or geophysical data. This infrastructure allows easy integration of additional data servers and provides scalability by geographically dividing both indexing and the data, which localizes network traffic.

The second component focuses on the relationship between the user and the wearable computer. In a spatial cognition aid, it can be useful for the user if she can navigate a virtual model of the surrounding environment for the study and exploration of areas prior to travel. Two classes of wearable computer interfaces were prototyped and evaluated in user studies involving navigation tasks. The first class of interfaces were based on speech recognition, gesture recognition, or a combination of speech and gesture. This study revealed issues with recognition and environmental lighting conditions with the particular form of video based gesture recognition employed. However, speech recognition provided a relatively effective interface. The second class of interfaces used isometric joysticks and tilt sensors as input devices, and employed various one and two handed control mappings. While there were some discomfort issues with isometric joysticks, the study determined that an aircraft-like control mapping, with steering in the dominant hand and speed in the non-dominant hand, was most effective. These interface explorations provide some background information and guidelines for designing navigation controls for use in spatial cognition aids.

The third component examined how wearable computers can mediate the relationship between the user and the environment in order to improve spatial cognition. Several studies were performed to determine how wearable computers can help users perceive and learn the layout of the surrounding environment. These studies investigated how environmental information should be presented to the user, and whether any effect on spatial cognition can be observed. These studies determined that an effective presentation provides an image of the surrounding environment that is rendered from a top-down viewpoint. That imagery should also be aligned with the user's head direction. Furthermore, since a wearable computer user's attention is divided between the real world and the computer display, techniques should be employed to help the user correlate infrequent views of the computer display. These include using a wide field of view to provide a stable set of landmarks and providing route markers to show the shape of the user's route and the user's progress.

While wearable computer researchers have examined related applications such as navigation aids, tourist guides, and surveying tools, few, if any, have examined spatial cognition aids, which are a distinct and important wearable computer application. Spatial cognition aids are focused on helping the user learn the layout of an area, rather than guiding navigation, providing tourist information, or modeling objects in the environment. This dissertation provides a demonstration of a viable and effective wearable computer based spatial cognition aid. It also provides guidelines, verified in user studies, of how to present environmental information in a wearable computer based spatial cognition aid. Other contributions also include a scalable server infrastructure, studies and guidelines concerning multimodal and two handed interaction design, and the conceptual model for wearable computer applications.

CHAPTER I

INTRODUCTION AND MOTIVATION

My father would sometimes tell me stories about his days as a Boy Scout in Florida. One story was about the father of one of the other boys in the Scout troop. This man displayed an uncanny sense of direction. No matter where he was, no matter the weather or time of day, he always knew which direction was north and he always knew the direction to his home. One dark night, a group of boys got together to test his direction finding ability. The boys quietly massed around the tent where the father was sleeping. They quickly dashed inside, picked up the sleeping cot, and carried the father on a crazy journey around trees, up and down hills, and around and around in circles. After thoroughly scrambling the father, they set him down and asked him to point north. The father pointed. They asked him to point home. The father pointed again. The boys consulted their maps and their compasses. Eerily, he was correct on both counts. He demonstrated an almost supernatural sense of direction.

I was quite impressed with this story. As a Boy Scout, I could navigate through the woods with map and compass, but I never displayed that intuitive feel for direction. Perhaps it is no coincidence that my father made a very nice pouch for me to carry my compass around my neck.

This lack of navigation sense also affected my ability to get around the city. When I moved to Los Angeles to attend college, I often got turned around and completely lost. Once I left the freeway, I would often get confused, miss turns, and have to retrace my route back to the freeway to start over. I was never able to visualize the structure of the LA freeway system very well, nor could I recall the layout of the streets of Pasadena where I lived. When I moved to Atlanta for graduate school, this problem continued. If someone described the location of a particular place in reference to particular areas of town, I was befuddled.

I started to wonder why I was having so much trouble navigating in urban environments like Atlanta and Los Angeles (Figures 1 and 2). While these cities are complex environments with intricate networks of streets and highways, some individuals have a lot less difficulty. I realized that

Figure 1: The complex urban environment of Atlanta.

Figure 2: The complex urban environment of Los Angeles (courtesy Annie Muske-Dukes).

I was having difficulty building up and maintaining a mental image of the city's layout. I seemed to be only able to memorize routes, and sometime only with difficulty. It was also hard for me to determine the cardinal directions: north, south, east, and west, while I was traveling.

Once I began to understand the limitations of my navigation skills, I thought that others might also have similar difficulties. In informal discussions with others, I learned of various techniques people used to develop familiarity after moving to a new area. Some study a map carefully and then venture out. Others carry a map while exploring, trying to keep track of where they are in the world and on the map. Still others test themselves by wandering around the new area until they feel almost lost and then try to find their way back. I found these diverse strategies very interesting for several reasons. These strategies reveal great creativity in developing coping mechanisms against poor navigation sense. They also highlight that exploration of a new area is a very common experience, and a problematic one.

I also considered individuals in special circumstances for whom understanding the environment is vital for their career. Law enforcement, military units, and emergency responders may be exposed to unfamiliar locations, but need an immediate and detailed understanding of their surroundings. This understanding allows them to travel to particular locations quickly and efficiently, communicate effectively, understand the locations of co-workers, and coordinate activities across a wide area. In these situations, understanding the environment can be more difficult than under normal conditions and the consequences for failure can be great.

These experiences and musings led me to investigate technological means to augment an individual's ability to perceive, understand, and remember the structure of the surrounding environment. A brief introduction to spatial cognition and mental maps will further motivate the need for such research.

1.1 Spatial Cognition and Mental Maps

Spatial cognition is the ability to perceive and comprehend the structure of the environment and to make decisions based on that knowledge. This is the mental facility that allow individuals to successfully understand and deal with the physical world, whether it is a single object, a single room, a house, or a city. In this dissertation, I have focused on supporting spatial cognition of large outdoor environments, rather than smaller indoor environments.

Understanding large geographic regions like college campuses, neighborhoods, or cities is quite different and often more challenging than understanding the spatial relationships between objects on a desktop or in a single room. Such outdoor environments are too large and too complex to perceive all at once. Accordingly, outdoor environments require the formation and use of a mental model, also known as a cognitive map or mental map. All of these mental processes are quite complex and cause spatial learning to be a slow and error prone process. Perhaps computer based techniques and artifacts can be employed to increase the rate of spatial learning and improve the accuracy of the mental map.

In this dissertation, I have pursued the development of a computer based spatial cognition aid. Such aids would help individuals learn their environment and develop good mental maps. Since these mental maps are the basis of navigation and a number of other spatial behaviors, such spatial cognition aids would help humans deal more effectively with their environment.

One might argue that such mental models should be the domain of the computer. The computer should maintain the model of the environment and give navigational assistance and directions to the user. In accordance with this viewpoint are a number of computer based navigation aids such as Map-in-the-Hat [149] and Walkmap [78, 147]. While such navigation aids are quite useful, the differences between a spatial cognition aid and a navigation aid should be highlighted. It will then be apparent that spatial cognition aids also have an important role that is distinct from navigation aids.

One could view the difference between a navigation aid and a spatial cognition aid in terms of a proverb often attributed to Lao Tzu: “Give a man a fish and you feed him for a day. Teach him how to fish and you feed him for a lifetime.” A navigation aid tells a user how to make a particular turn while following a route to a particular endpoint. A spatial cognition aid would help a user learn the layout of the environment. The spatial cognition aid would help the user develop the knowledge to determine the routes to any point for themselves. It is not necessarily the case that a navigation aid would help a user learn the layout of the environment. The navigation aid solves a specific task, but a spatial cognition aid would imbue survey knowledge, which is a more general tool.

Another problem with computer based navigation aids is the interaction required to select a destination and particular points on the route. If the computer maintains the mental model of the environment, the user must interact with the computer to decide on new routes and new destinations. A good mental map, previously developed with a spatial cognition aid requires no such interaction for ad hoc path planning. A good mental map could be especially useful for police or military personnel who must quickly learn to patrol a new area, or a marathon runner or cyclist who must anticipate changes in terrain to effectively race against others. For these individuals, interacting with a navigational aid would be a distraction that could prevent them from perceiving sudden and significant events occurring around them.

Navigational aids might also induce over reliance as documented in previous wearable computer use for aircraft inspection [98, 97]. Users may begin to rely too heavily on the aid and surrender navigation authority and decision making to the aid. This can become a problem if the navigation aid has a malfunction or its information is incomplete or becomes out of date. The user may be literally led astray. By surrendering navigational authority, the user may be less able to recognize that they are lost until too late, and may be less able to recover and find their own way back. Furthermore, a long term reliance on these navigation aids may cause users to stop refining and adding to their mental maps, and even begin forgetting. An analogy would be an individual who relies on a spouse that always drives and always navigates. After a time, the individual could find it more and more difficult to find his own way around or to give others directions.

A good spatial cognition aid would also have personal and emotional significance. It could imbue a traveler with a higher level of confidence. They would not have to worry about becoming lost because they "know" the area. Furthermore, a spatial cognition aid might help individuals compensate for cities with poor imagability. That is, cities whose layouts are especially difficult to understand, due to geography, city planning, or other factors. In *The Image of the City*, Lynch suggested that cities with poor imagability lead to confusion, less sense of place, and a poorer quality of life [83].

1.2 How can Wearables Support Spatial Cognition?

A wearable computer is a mobile, unobtrusive, and continuously available computational resource. It is often equipped with a head mounted display, wireless networking, and possibly a GPS unit or

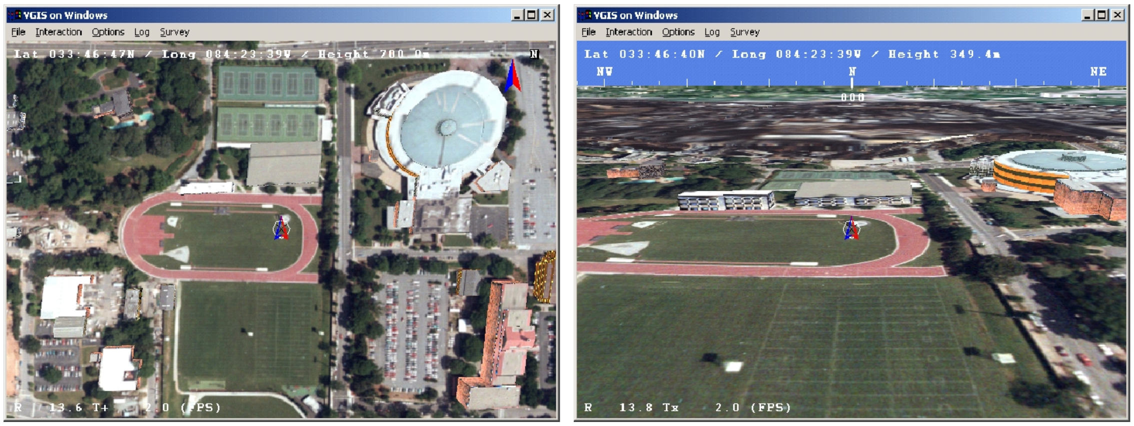


Figure 3: Examples of top-down (left) and perspective (right) viewpoints.

other technology for positioning. With these features, it can be a platform for a various applications that use location based information, such as a spatial cognition aid. This would be a tool that allows a user to explore a new area while helping the user perceive and learn the structure and layout of the environment. Such a prototype spatial cognition aid was built for this dissertation.

Since individuals need help in placing their location into a larger context, the prototype spatial cognition aid rendered a virtual model of the environment in the eyeglass mounted display, providing an image of the user's surroundings. This overview imagery can allow the user to see the spatial relationships between landmarks and geographic features that were previously difficult to perceive as an earthbound traveler. This is in agreement with previous work has shown that prior studying of a map is helpful in developing survey knowledge [152, 151]. Furthermore, providing this overview imagery as an individual is exploring the environment allows the individual to correlate the vistas, the natural first person views of the environment, into the structure of the overview. This process should be analogous, yet faster, than the numerous egocentric traversals typically required to develop the mental quiltwork that forms exocentric survey knowledge.

A virtual model of the surroundings can be presented to the user with several possible viewpoints. A top-down, overhead view is a simple viewpoint that is used in many paper maps (see

Figure 3, left). This was chosen as a candidate since it can clearly show the layout of the surrounding environment. Another approach would be to present the imagery in such a way that it is aligned with and overlaid on the user's first person view of the world. This would use augmented reality techniques to register, or align real and virtual imagery. However, this approach was considered and rejected for several reasons. Technology limitations in position and orientation accuracy make it difficult to correctly register the virtual imagery with the real world. These discrepancies would detract from the augmented reality experience. Furthermore, an augmented first person view would not provide as much additional information about the layout of the environment as an top-down, overhead view.

Another possible viewpoint is a perspective view which is somewhere between an overhead view and a first person view (see Figure 3, right). It places the viewpoint above and behind the user's location. The viewpoint seemed potentially helpful to a user learning the structure of the environment. It also seemed possible that it would help the user learn and recognize building facades and silhouettes of terrain and buildings. Accordingly, this perspective viewpoint was included in the dissertation investigations. However, a preliminary study showed that the perspective viewpoint was distracting to the user and interfered with the user's ability to remember the surroundings. It may potentially affect the user's ability to perform other tasks. As it turned out, the most effective presentation evaluated in this dissertation provided a top-down viewpoint.

Another important presentation factor is orientation. A fixed orientation such as north alignment can be used, or the overview can be rotated to align with the user's forward direction. Levine [79, 80] suggests that aligning a map with the user's forward direction is more effective since it is easier for the user to correlate features on the map with features in the user's surroundings. However, there can be some concern about the movement and rotations involved in aligning the overview imagery. These rotations can create large changes in the display image which may be distracting to the user and make the imagery more difficult to memorize. However, some evidence suggests that using a fixed orientation map while traveling may significantly impede learning [165]. The most effective presentation from this dissertation was in accordance with this last finding, and used imagery that was aligned with the user's head direction.

A final issue, the division of user attention, emerged during the later portion of the dissertation work. Users must pay attention to the physical world as they walk since they wish to avoid obstacles and learn their surroundings. They must also pay attention to the wearable computer in order to learn the overall configuration of the area and see where they are currently located on the map. This division of attention can cause users to shift their attention back and forth between the physical world and the wearable computer display. It can be difficult for the user to perceive and understand her progress on the display with these infrequent glances at the display. The most effective presentation provided two features to address this division of attention issue. First, a wide field of view was used. This presented a stable set of landmarks that may have helped users correlate their infrequent glances at the display. Second, a trail was displayed which allowed users to perceive the shape of their journey as well as their most recent progress on the map and correlate that with their progress in the world.

1.3 Thesis Statement

A wearable computer with an eyeglass mounted display can provide imagery for environmental context, and thus improve an individual's ability to perceive, understand, and recall the spatial layout of an outdoor environment. Furthermore, an effective presentation of this environmental imagery will be head oriented, rendered from a top-down viewpoint, and must take into account the divided attention of wearable computer users.

1.4 Contribution Statement

This dissertation provides several primary contributions regarding wearable computer based spatial cognition aids.

While maps are a common spatial cognition aid, there are few spatial cognition aids implemented as wearable computer applications. With few, if any, instances, it is not surprising that there are no prior studies investigating the effect of wearable computers on spatial cognition. This dissertation provides an example of a wearable computer based spatial cognition aid. Furthermore, it details user studies showing that this spatial cognition aid is effective and helped users learn the layout of an outdoor environment.

The studies performed for this dissertation also investigated how environmental information should be presented to the user in such an application. These studies also produced experimentally verified guidelines for design issues such as viewpoint, orientation, distraction, and divided user attention. Previously, no studies had examined such design issues for wearable computer based spatial cognition aids.

This dissertation also makes some secondary contributions that provide support for the development of spatial cognition aids and other wearable computer applications that use location based information.

A wearable computer needs to gather information about the environment for spatial cognition aids and a variety of other environment aware applications. This dissertation describes a scalable server infrastructure that can be used to distribute geospatial information. This infrastructure provides scalability by geographically distributing both indexing and data.

This dissertation also discusses some interaction techniques that can be used for interacting with applications that provide virtual models of an environment, like spatial cognition aids and navigation aids. Effective interaction is important since users need to be able to easily study and examine the virtual model of the environment. Users may also need to search for particular features and preview areas prior to visiting them. Some guidelines for multimodal and two handed interaction design are discussed.

Finally, a conceptual model for wearable computing applications is described. This model envisions wearable computers as a mediator between users, other individuals, and the environment. The model can be a useful tool for designers who need to understand the design scope of a wearable computer application and the various interactions involved. This conceptual model also provides a design framework for the development of the spatial cognition aid and the work performed for this dissertation.

1.5 Dissertation Organization

In this introduction, I presented the notion of wearable computers as an aid to learning and understanding a complex outdoor environment. In the remainder of this dissertation, I will elaborate on this notion by discussing various design issues, experiments, and infrastructure necessary in developing this type of wearable computer application.

Chapter II will discuss spatial cognition theories and methods of investigation. Some previous work in spatial cognition and computing will be presented.

Chapter III will present a conceptual model for wearable computing as a mediation of relationships between users, other individuals, and the environments. This model is used to frame the following chapters and describe how they form the basis of a wearable computer system for spatial cognition.

Chapter IV will describe a geographically based, scalable server infrastructure to distribute location based information, such as the location of individuals, terrain data, or weather conditions, to wearable computers.

In **Chapter V**, the need for alternative wearable computer interaction techniques will be discussed. Evaluations of multimodal and two handed navigation techniques for a wearable computer based visualization will be described.

Chapter VI will demonstrate that wearable computers can aid an individual's spatial cognition. It will also describe experiments that were conducted to determine how wearable computers should present information to aid spatial cognition.

In the conclusion, **Chapter VII**, I will summarize the main contributions of this dissertation, and discuss possible areas for future work.

CHAPTER II

SPATIAL COGNITION AND RELATED WORK

Since understanding and navigating outdoor environments is a fundamental part of daily life, it is not surprising that a spatial cognition has a sizeable body of investigation and research. This research cuts across a number of different research communities including cognitive psychology, engineering psychology, geography, industrial engineering, and computer science.

In this chapter, I will first discuss background material in spatial cognition. This includes relevant theories of spatial cognition, different techniques for measuring spatial cognition, and potential design guidelines for navigation and spatial cognition aids.

I will then discuss the use of computing devices that support spatial behaviors such as navigation and spatial cognition. This includes the use of virtual reality for both the study of spatial cognition and the training of an individual's spatial abilities, and the use of mobile and wearable computers for navigation, spatial cognition, and other environment related applications.

2.1 Theories of Spatial Cognition

A significant and pioneering work in spatial cognition is Kevin Lynch's 1960 MIT dissertation in city planning entitled *The Image of the City* [83]. In this work, Lynch attempted to determine characteristics that made it possible for individuals to perceive, develop, and maintain a mental image of their own city. He postulated five urban elements, now sometimes called Lynchian elements, that form a design palette for a city that is easy to mentally visualize.

Paths: Paths are channels through which people move. These can include roads, walkways, and transit lines. It is from paths that individuals view the other elements of the environment.

Edges: Edges are linear elements that delineate different regions. They may be barriers such as walls or shorelines, or merely seams between two different regions.

Districts: Districts are sections of a city that have a unifying and identifying theme. A district is identifiable from inside the district, and may be used a reference point from the outside.

Nodes: Nodes are locations of strategic importance. This importance can come from junctions of paths, terminal points in transportation lines, or concentration points for human activity, such as a city square or street corner hangout.

Landmarks: Landmarks are reference points. These are typically physical structures such as buildings, signs, monuments, or distinctive natural features. These landmarks may be tall, distant, and observable from a variety of locations, or landmarks may be local and might only be seen from a small area or particular approach.

These elements were culled from interviews of residents from Boston, Jersey City, and Los Angeles. With well defined and memorable districts, Boston appeared to be the most "legible" or "imagable" of the three cities that Lynch examined. However, there were still several imagability issues with Boston such as particular primary roads that curved in confusing ways and had unclear intersections.

Lynch argued that urban planners should try to develop cities that were imagable or legible to the inhabitants. This concept of legibility of a city is closely related to the notion of spatial knowledge and mental maps. Lynch felt that a legible cities would provide a better quality of life for its citizens.

A number of researcher have attempted to verify if these Lynchian elements exist and if they are distinct, complete, and universal mental concepts. For example, Norberg-Schulz's 1971 work suggested that there are only three elements: place, path, and domain [96]. However, Magaña's 1978 dissertation [85] examined the mental models of residents of Guadalajara, Mexico, and suggested that Lynch's elements were valid. In 1995, Aragones and Arredondo [2] examined the existence of these elements for Madrid residents, and found that the edge element was somewhat ambiguous. This long lived debate over the mental images of urban environments is evidence that Lynch's work has sparked a great deal of interest in spatial cognition.

In developmental psychology, Piaget's work [105] suggests that individuals mature through four levels of spatial cognitive development. These levels characterize the spatial frame of reference that the individual uses to understand their surrounding environment, as well as the spatial operations that can be comprehended and performed.

Sensorimotor: The sensorimotor level is experienced from birth to approximately age 2. The world is experienced through sense impressions, so a spatial frame of reference is not a relevant concept.

Preoperational: In the preoperational state, children of age 2-6 years understand the environment from an egocentric frame of reference. They locate objects in reference to their own bodies. They only recognize objects from familiar perspectives. They understand such spatial relations as proximity, separation, open/close, between, and order.

Concrete Operational: The concrete operational level (ages 7-9) is characterized by a fixed frame of reference. Children in this level have a fixed coordinate system that is oriented and aligned on static landmarks such as home, school, or church. For example, the child may only be able to find the way home in reference to known landmarks such as school. They can recognize landmark objects from multiple perspectives and understand spatial concepts such as enclosure, continuity, and geometry.

Formal Operations: In the formal operations stage, which develops around 11 years of age, individuals can understand coordinate systems that are not centered on the body, or familiar landmarks. These include coordinate systems such as the cardinal directions, latitude and longitude, polar coordinates, and map grid systems. Individuals can understand such spatial operations such as proportional scale, reduction, distance estimates, and use of coordinates.

While Piaget's theory of spatial cognitive development explains how an individual's general spatial abilities develop over a lifetime, Thorndyke's theory of spatial learning suggests how an individual's mental representation of a particular environment changes over a shorter period of time. This mental representation, also known as a spatial representation, cognitive map, or mental map, allows individuals to perform a variety of spatial activities. These activities include recognizing one's location, determining the direction, distance, and route to another location, or communicating with others about directions to other locations.

Thorndyke's theory of spatial learning suggests that individuals develop three levels of spatial knowledge as they experience a new environment:

Landmark Knowledge: This type of knowledge allows individuals to recognize particular landmarks or places. This knowledge can be gained by first hand experience of the location, or second hand experience, such as by viewing video or photographs.

Route or Procedural Knowledge: This type of knowledge represents the procedures and information needed to follow particular routes. This includes a description of the actions necessary to follow the route, features encountered along the route, distances between locations along the route, and changes in orientation, such as turns. This is a thread of information that connects isolated perceptions of landmarks.

Survey or Configurational Knowledge: Survey knowledge provides a map-like model of the environment. While it continues to be debated as to whether this knowledge is actually stored as a map-like image, a set of declarations about the environment, or some other format in the mind, it does seem to have some map-like qualities. The locations and distances between landmarks and other locations appear to be available in an exocentric, fixed frame of reference. This allows individuals to describe the location of any landmark relative to any other landmark. This differs from landmark knowledge and procedural knowledge which are typically formulated with an egocentric frame of reference. This enables the individual to plan, describe, and follow routes never before taken. This type of knowledge can be gained over time by repeated experience in the environment, or indirectly, through the study of maps.

These levels of knowledge are somewhat representative of the progression of an individual's spatial knowledge. For example, an individual would first begin to remember particular landmarks. After a time, perhaps routes between work and home would be memorized. Later, after many travels through the area, the individual would gain a good sense of the layout of the neighborhood or city. However, these spatial knowledge levels are not mutually exclusive and may be developed slightly out of order. For example, one can study a map without traveling through the environment. The individual would gain a level of survey knowledge, but not have good route knowledge. With only map experience, the individual would be less able to recognize the appropriate paths and turning points in the world.

It is typically held that survey knowledge is the most robust and most useful type of knowledge. A detailed mental map of the environment with survey knowledge can allow someone to plan and traverse new routes that have never been taken before. This is important if new obstacles are encountered and a new route must be taken, or if the individual makes a wrong turn. Route knowledge can be brittle, making recovery after that wrong turn difficult.

Stevens [142] determined that mental maps appear to be hierarchical. The hierarchy can be based in part on political, cultural, or structural information. These hierarchies allow simplifications in encoding the mental map. For example, many individuals feel that Reno lies east of San Diego since the state of Nevada lies east of California. While this is an inaccurate notion of the relative locations of the cities, it reveals a common simplification in the mental model of the western US. Since the state of California lies on the western border of Nevada, one could assume that any city within California lies to the west of any city within Nevada. Other types of spatial distortions and omissions can be measured and may contain a great deal of insight into an individual's mental map.

The characterizations of spatial knowledge from Lynch, Stevens, and others can serve as an important guide in determining the level, detail, and accuracy of an individual's mental map. In the following section, various techniques for evaluating an individual's mental map will be discussed.

2.2 Measurement of Mental Maps

When introducing a new training method or device, it is important to evaluate the effects of the newly introduced artifact. The difficulty with spatial learning, as with many psychological constructs, is that the mental map is contained entirely within the mind and is difficult to measure. One potential approach is to use physiological measures. However, physiological measures for learning could require potentially expensive and complex equipment for procedures such as electroencephalography (ECG) and magnetic resonance imaging (MRI). Furthermore, since spatial cognition appears to be a high level brain function, these physiological measures will not detail the content of the mental map. While one can determine the regions of the brain involved in specific spatial behaviors, it is not apparent that a mental map has a topological analogue within the brain that can be imaged.

However, a variety of other, non-physiological, experimental techniques have been used to characterize an individual's mental map. One class of techniques begins by prompting the study participant with some incomplete information and asking the participant to provide additional context or details. For example, the individual may be shown a photograph of a landmark and be asked to place the landmark on a map. A second approach is to have the individual provide information through free recall, providing less prompting. For example, the study participant may be given a blank sheet of paper and asked to draw a map of their surroundings or provide a written description of a route.

The approach taken may depend on the level of detail and type of information that is required in the study, or logistical decisions. An prompted technique may allow the study to focus on a particular detail or characteristic of the mental map. An unprompted technique may provide less control over the information that is recalled, but may uncover interesting and unanticipated data. Prompted techniques can be easier to analyze. Some techniques can interfere with the study participant's experimental task. Some unprompted techniques include:

Interviews: Participants are asked to describe the layout of particular areas. The accuracy and detail of their responses indicates the quality and depth of the mental map. Interviews were used by Lynch [83] in his 1960 dissertation work on city legibility. Participant responses may be affected by the interviewer. Care must be taken to provide objective analysis of the results.

Giving Directions: Participants are asked to give verbal directions from a particular point to a destination. The language used in the directions can suggest how the participant has encoded their mental map. Coding and analyzing the results can be involved.

Map Sketching: Participants are asked to make a sketch of the area. The map can be examined for detail, omissions, and geometric distortions. Map sketches were also used by Lynch [83]. Billinghurst and Weghorst [17], as well as Darken [29], employed sketch maps for understanding cognitive maps of virtual environments. Map sketches may be affected by a participant's drawing skill. Comparisons between sketches may require adjustments for differences in scale and distortion.

Map Reconstruction: Participants are asked to place tokens on a board to recreate the relative positions of landmarks. As in map sketching, the reconstruction can be examined for geometric distortions [46].

Some prompted techniques for characterizing an individual's level of spatial knowledge include:

Landmark Identification: After traveling a route through an environment, the participant is shown pictures of landmarks. The participant is asked to determine if those landmarks were on the route taken. This technique only measures landmark knowledge.

Locating Landmarks or Vistas on a Map: After traveling a route through an environment, the participant is shown pictures of landmarks or vistas. The participant is asked to locate the depicted scenes on a map.

Estimating distance and/or direction between landmarks: After traveling a route through an environment, the participant is shown pictures of two landmarks. The participant is asked to determine direction and/or distance between the landmarks. This was used in a number of studies including Golledge [48] and Gärling [44]. One variation on this approach is to have a participant estimate the length covered by particular route. Another variation is stop the participant at various points during the route to estimate distance and direction to the starting point. This last variation may interrupt the participant's travel experience and affect results.

2.3 Guidelines for Spatial Cognition Aids

Some previous research has suggested guidelines for the presentation of spatial information. This research can suggest possible areas of investigation for the design of a spatial cognition aid for this dissertation.

One simple spatial cognition aid is a "You are here map". These maps are provided in such places as shopping malls, company and school campuses, and large office buildings. Levine's work with "You are here maps" [79, 80] suggests the following design rules for effective YAH maps:

- The two-point theorem states that a map reader must be able to relate two points on the map to their corresponding two points in the environment.

- The alignment principle states that the map should be aligned with the terrain. A line between any two points in space should be parallel to the line between those two points on the map.
- The forward-up principle states that the upward direction on a map (assuming it is mounted perpendicular to the floor) must always show what is in front of the viewer.

Work done in automobile navigation systems also suggests some guidelines for spatial information presentation. Spoerri developed and evaluated a prototype automobile navigation display that presented a series of turns [135]. Users were asked to remember and later reproduce the series of turns. He found that directions presented with a perspective viewpoint, and in a user centered coordinate system, were easier to recall than a top-down view in a global (north aligned) display. He concluded that such displays would allow drivers to more easily integrate the directions with what they are seeing through the windshield. Another study of automobile navigation systems by Mashimo et al. [89], divided university students into two groups, a Fixing Group and a Rotating Group, based on how they drew a map of their school. The researchers felt that rotating or not rotating the map while drawing was suggestive of the students' spatial orientation, and thus how the students perceived and recalled their environment. In the driving portion of the study, participants were asked drive a route while following a map presented on an automobile navigation system. The system could display either a north-up map or a heading-up map. While only 4 students from each group participated in the driving portion, an interesting result is that participants in Fixing Group pointed out positive aspects about the north-up presentation. Members of the Rotating Group pointed out negative aspects of the north-up presentation. The authors did not provide any characterization of comments about the heading-up presentation. Mashimo et al. concluded that the display presentation should be adapted to the driver's spatial orientation.

Aretz and Wickens studied the mental transformations required in a navigational checking task [3]. This task is often performed by pilots who must determine if an electronic map is congruent to their current location. Two experiments were designed to determine the amount of mental processing required to determine if a particular electronic map was congruent with another scene. These experiments presented simplified scenes with both top down and perspective viewpoints. A map was presented with some rotation angle. The time required for the subject to respond with a congruent or non-congruent determination was measured. The experiments showed that humans had the fastest performance if map and the scene were visible at the same time, and the map is given a forward up alignment, rather than a north up or other alignment.

2.4 Computing and Spatial Behavior

Computing artifacts have been used to support human behavior in the physical world for hundreds of years. Sextants, clocks, compasses, and slide rules are a few of the mechanical and optical computing aids that support navigation in the physical world. GPS and other radio and satellite navigation systems are a few examples of electronic computing aids for navigation.

With the development of 3D computer technologies, it became possible for humans to become lost, not just in the real world, but also in virtual spaces, such as virtual reality environments, visualization environments, and 3D computer games. Becoming disoriented in a virtual environment is problematic, but the situation is far worse in the real world. Terminating the program, restarting, or reinitializing, the system are not viable alternatives in the real world.

Since humans can become lost in the physical world and in virtual worlds, computing artifacts have been designed to assist users in those specific environments. Furthermore, due to the relative ease of simulating locales and travel, virtual reality has also provided a tool for the study of human spatial cognition. In the following sections, related work in computing, navigation, and spatial cognition will be discussed.

2.4.1 Virtual Spaces: Spatial Behavior and Virtual Reality

Advanced to its furthest imaginable state, virtual reality could provide a simulation of the real world such that any experience in VR would be indistinguishable from any real world experience. With such a virtual environment, an individual's spatial behavior would be identical to that in the real world. However, today's virtual environments are unable to faithfully duplicate real world. Even so, it may be possible for virtual environments to support certain aspects of spatial behavior.

Kaplan and Kaplan [63] suggested that spatial behavior could be studied in both real and simulated settings. This has been employed in many studies. Goldin and Thorndyke used a film to simulate navigation [47] and concluded that simulated navigation can sometimes substitute for real navigation. Other studies have used sequences of photographs to simulate travel.

One example of a virtual reality tool for studying spatial cognition is the VR Navigation Research Tool (VRNRT) [156]. This tool provides a demographic survey, tools for building and populating a 3D maze, a camera path designer, and logging tools. The test environment was made available to users over the World Wide Web. This suite allows construction of various scenarios to explore wayfinding, navigational knowledge, and navigational decision making.

Some issues with simulated environments have been raised by Evans and Gärling [39]. Real world environments have factors such as weather conditions and human activity. These may provide additional cues and meanings that may influence behavior. Differences in perception also exist between real and virtual environments. Some of these differences include display resolution, field of view, color, contrast, stereoscopy, correct perspective, and environmental detail, among others. Differences in locomotion, acceleration, speed, and interaction may also reduce a number of cues. These factors may affect an individual's experience and harm spatial cognition.

Most of the work involving spatial cognition and virtual reality has focused on improving navigation and wayfinding, either in virtual environments themselves, or in the real world through prior training in virtual environments.

A number of researchers have used virtual reality to train individuals in order to improve performance in the physical world. Witmer et al. [166] were able to use a virtual model of an office building to train route knowledge and improve performance in the real environment. Darken and Banker [30] also examined the transfer of spatial knowledge, but in an outdoor orienteering course. Participants with various levels of navigation skills were given training with a map, a virtual model of the outdoor environment, or exposure to the real environment. Performance was most affected by navigation skill level, but the virtual environment had benefits since more area could be covered in a shorter period of time. However, the virtual environment training had the most performance benefit for those with intermediate navigation skills. No benefit over map use was found for beginner or expert navigators.

Goerger, Darken, and others [46] performed a study examining the effect of virtual environment training combined with map study. Participants studied the floor plan of an indoor office environment, or studied the floor plan and a high fidelity virtual environment. However, floor plan study alone appeared to be more effective than studying the floor plan and using the virtual environment. The researchers theorized that short exposure times (30 minutes in this study) and complex models may in fact be detrimental to performance. This was supported by Waller et al. [159], who examined the transfer of spatial knowledge from a virtual maze to a real world maze. The study found that real world performance after a short duration training in a virtual environment was no better than map study. However, long duration training in a virtual environment produced better performance than real world training.

Navigation performance and spatial cognition are also important issues in 3D computer generated environments. These environments may include 3D games, 3D architectural or engineering applications, and scientific visualizations. Accordingly, there is a lot of interest in applying what is known about spatial cognition to to improve performance inside these virtual environments.

Darken's Ph.D. dissertation focused on design principles for effective navigation in large scale virtual environments [29]. He postulated that real world wayfinding and environmental design principles could be effectively employed in virtual environments. Two types of principles were proposed: environmental design principles and map presentation and use principles. The environmental design principles are:

1. Divide the world into smaller regions, in a hierarchical fashion.

2. Organize the small parts under a simple organizational principle.

3. Provide frequent directional cues.

The map presentation principles are:

1. Show the organizational elements (such as the Lynchian elements) and the organizational principle used.

2. Show the observer's position.

3. Orient the map so the observer's forward direction is up.

These principles were examined by by comparing performance in four different treatment groups. These groups include a control treatment that lacked wayfinding assistance, a grid treatment which used environmental design principles, a map treatment that used map presentation principles, and a map/grid treatment that used both sets of principles. By using such measures as "Think Aloud", map sketch, search time, and search distance, these design principles were shown to be effective.

Other work in virtual reality employs spatial cognition concepts to help performance inside virtual environments. Vinson provided guidelines for landmark design for virtual environments [157]. He suggested the use of Lynchian elements and additional guidelines he developed for color, shape, size, placement, and alignment of landmarks.

Other researchers have examined other types of maps and representations of the environment for navigation assistance. Ramlool and Mowat [112] provided a schematic or symbolic representation of the virtual space. As a user navigates a VRML world, a cognitive map representation of the world is constructed by the navigation application. This representation is constructed using Space Structure Diagrams, which reduce the environment to a series of nodes representing rooms, and arrows representing transitions between those rooms. This cognitive representation allows users to see the logical organization of space and interact with the representation for navigation.

Another useful map representation is the worlds in miniature concept. A number of variations on the worlds in miniature concept have been developed [143, 103, 37]. This tool is a miniature model of the larger virtual environment that can be used to provide navigation information, as well as providing new interaction techniques for navigation and object manipulation. A related concept is that of the toolglass [16, 155, 145, 144], which can provide a small, planar image view of a virtual environment from another perspective. It can also be used to navigation information and interactive navigation techniques. Both of these representations may allow the user to gain a better idea of their location and the layout of the virtual environment.

2.4.2 Physical Spaces: Spatial Behavior and Mobile and Wearable Computers

There are four major functional classes for computer based aids for spatial information. The first class is that of a wayfinding or navigation guide that helps a user follow a particular route or proceed to a particular landmark or waypoint. These devices may use compasses or GPS to guide a user from their current location to another. An example would be a dashboard car navigation system or a hiker navigating by a GPS unit.

The second type of aid is that of an information guide or tourist guides that provides location based information. While these information guides may provide some route guidance, they are designed to support more abstract goals than mere wayfinding. They provide additional, non-geographic information that may be of interest to tourists, such as historical commentary, information about current building occupants, or current or future activities that may be scheduled.

A third class are spatial cognition aids. These focus on assisting the user in learning the structure and layout of the environment. They can do this by providing geographic context for the user, typically in the form of an overview map with the user's current location indicated. The location of other buildings, landmarks, roads, or other relevant geographic features are also indicated. Relative locations of other collaborators may also be present.

A fourth type of aid allows the creation or capture of spatial information. A wearable computer for surveying roads, creating 3D models of real buildings, or recording the route of the wearer would fall into this category. Another example would be a handheld computer for making annotations on a map, such as for recording archaeological data or tourist information.

Certainly, any given system might have characteristics of more than one of these categories, but these categories are representative of the major goal of a given system. A large number of projects appear to fall into the first type, navigation guides. There are also very notable tourist guides of the second type. A number of interesting interaction techniques for modeling and surveying, are seen in surveying aids of the fourth type. This dissertation developed and evaluated a spatial cognition aid of the third type, which provides geographic context and supports spatial learning.

There are a large number of navigation and wayfinding guides. Some were exploratory applications to determine the potential of mobile or wearable computers. Others are wayfinding devices for the users with disabilities.

Metronaut was a mobile computer, developed at Carnegie-Mellon, that provided scheduling and navigation features. Scanning event bar codes would allow the user to add new events to his schedule. The user could also receive directions to the event. The user would input his current position into the computer by scanning bar codes on information signs that were placed around campus. A set of directions would then be displayed on the screen.

The "map-in-the-hat" system developed by Thomas, et al. [149], was a wearable computer based navigational aid system. It used a see-through head mounted display to display way-points and a compass for walking direction. The main focus of “map-in-the-hat” was to guide the users in an orienteering task from one point to another. The display presented information in a first person, head tracked, point of view.

The Battlefield Augmented Reality System (BARS) was a system that was designed to address the needs of the dismounted soldier in urban landscapes [62]. This AR system presented data about the soldiers environment such as sniper positions or navigational waypoints based on the importance of each of the soldiers current tasks and needs. This system attempted to register virtual information on top of the physical objects, such as buildings, in the world. Another military related application was shown in Tinmith, a wearable computer research platform with a number of capabilities. A simulated combat training application was demonstrated where ModSAF simulated forces were displayed on a 2D overview map and a 3D augmented reality view in a headmounted display [106]. These military applications could show locations or units that should be avoided as well as ones that should be destinations.

Context Compass [146] and Walkmap [78] were wearable computer applications developed at the Nokia Research Center. Context compass was a linear compass that was augmented with objects of interest. These objects of interest were selected by facing the object, which centers the object in the compass. Each object had an associated URL with a web page, image, audio, or video. Walkmap was an overview 2D map that could be presented with a top down viewpoint or a perspective viewpoint. While the authors hoped that the perspective viewpoint would boost user performance in a wayfinding task, a very rudimentary evaluation failed to demonstrate this. In fact, users found the perspective map more difficult to use. In some sense, this dissertation revisited and reconfigured this task and experimental design.

Drishti [51] was a navigation system that used voice recognition and synthesis, GIS, and GPS components to assist the visually impaired and disabled. Temporal as well as location data was used to plot routes on the fly. Users were guided on these routes with synthesized speech. However, other research suggests that speech may not be the most effective output channel. An alternative is a haptic interface, an array of taping units that are worn on the back and to help the user maintain proper orientation during travel [38]. An evaluation by Ross found that using speech to provide orientation guidance to the user could be confusing [118]. Better success was found with the haptic interface since it could function under a variety of conditions including hearing loss and noise. Speech and spatialized sound interfaces were less robust under these conditions.

Tour guides and information guides comprise a second type of spatial cognition aids. While some may provide navigational information, they are largely focused on providing non-geographic information about a location, building, or district. This may include information about the occupants of a building, historical information, or location based entertainment.

Cyberguide [1] was an indoor and outdoor tour guide based on the Apple Newton handheld computer. The indoor version presented information about various demos within a lab environment. An array of infrared transmitters was used to pinpoint location within the lab. The outdoor version used GPS to present information about local bars and other establishments in Atlanta. A travel diary was created and used to suggest other locations that a user might be interested in visiting.

The Touring Machine and the Mobile Augmented Reality System (MARS) [41, 56, 57] was a wearable augmented reality system that presented multimedia information about the Columbia University campus with access to department web pages. It combined see-through augmented reality with tablet input and output. Historical information about the Columbia campus, such as multimedia clips and models of former buildings, were presented in location. Similar information was available in Archeoguide [158] an augmented reality tour guide for the Olympia archaeological site in Greece.

Aids that provide geographic context and support spatial learning form a third category. Such applications would provide some type of overview that provides information about spatial layout of objects and geographic features in the surrounding environment. There appear to be fewer examples of such aids. There seem to be even fewer evaluations of such aids. Two examples of this category may be Rockwell's ARscape and the U.S. Defense Department's LandWarrior navigation software.

Rockwell's ARscape [15] may be an example of a wearable computer application that provided geographic overview information. It is unclear exactly what tasks the software was designed to support, however, it might fit into this category. ARscape was a 3D terrain rendering program that provided a 30m resolution view of the area around Rockwell Science Center. The view was rendered on a workstation and then transmitted to the wearable computer. It could have been used to give a user a very good idea of the layout of the surrounding terrain.

LandWarrior [94] was an US Army project exploring new technologies for the dismounted soldier. One component of this project was an exploration of wearable computing. These soldiers were equipped with wearable computers, GPS units, a helmet mounted display, and map software that displayed both topographical maps and satellite photos. In conversations with a project engineer, I learned that during exercises, conventionally equipped soldiers learned to closely follow Land Warrior soldiers. The Land Warriors had gained a reputation for always knowing where they were and where they were going. This software appeared to provide a simple overview map in an overhead view with the wearer's location indicated. The project may have stumbled onto a spatial cognition aid. However, beyond some anecdotes, no evaluation of user performance seemed available. Nor did there seem to be a specification of how the map was oriented. Unfortunately, this project seemed unlikely to study spatial cognition in detail.

There are a number of different applications that fall into the category of surveying or spatial information capture. For example, Baillot et al. described a number of interactions that could be used to create 3D models with a mobile computers [7]. These were powerful enough to specify points, lines, extrusions, and simple 3D models that corresponded to objects in the world.

The Tinmith project also examined the problem of environmental modeling. Tinmith-Metro was a demonstration application that allowed users to perform a variety of city modeling tasks [107]. Constructive solid geometry (CSG) operations were used to create 3D objects. Existing 3D models could be placed interactively, and a variety of interaction techniques, from head tracking to two handed input, were used for interaction. In fact, it allowed a model to be viewed from a variety of viewpoints, including orbital, a rotating map view, and other body relative angles. Another technique in Tinmith-Metro was Bread Crumbs which could be used to model large outdoor ground features [108]. By dropping a number of markers as the user traverses a path, a enclosed polygon could be formed around large objects such as lakes and parking lots, or even roads, trails, and rivers. These polygons could be further edited with CSG and other operations.

Diaz proposed a wearable computer application that allowed semantic information about a space to be deduced and captured [34]. While computers and location tracking systems often describe space in terms of coordinates and distances, most humans describe regions of space with linguistic phrases, such as “computer science building” or “lunch area”. Diaz’s application analyzed documents created in a space for significant keywords, or, as in his prototype, take in manually assigned labels for that space. These keywords would describe the activities and purpose of that space. Users could search for specific types of space or quickly uncover that what type of space they were currently in.

Since mobile computing, and especially wearable computing, is in its infancy, most of these devices were technology demonstrations. That is, they were designed and built to show how what interesting abilities and functions might be made available. Certainly, there is plenty of room for additional evaluation of spatial aids. Furthermore, among these devices, spatial cognition aids seem to be few and far between.

2.5 Summary

In this chapter, background theories on spatial learning and spatial cognition were discussed. These theories have allowed the development of a number of techniques to characterize an individual’s cognitive map. There are also a number of research efforts that involve computing and spatial behavior. Virtual reality has been used to study spatial cognition and provide training to improve real work performance. There are also a number of mobile and wearable computing applications involving spatial behavior. However, most of these applications are focused on wayfinding, with a few others focused on tourist guides and surveying aids. This dissertation was focused on developing spatial cognition aids and supporting spatial learning, rather than navigation and wayfinding. In the following section, a model for wearable computer applications will be presented. This model will be used to outline the architecture of a spatial cognition aid for wearable computers. It will also lay out the structure of the rest of this dissertation.

CHAPTER III

A RELATIONSHIP MEDIATION MODEL FOR WEARABLE COMPUTER APPLICATIONS

3.1 Introduction

Wearable computers can play a more integral role in a user's life than desktop applications. Wearable computers go wherever their users go. Wearables are also in close physical proximity with the user, with input devices worn on the body and displays mounted in front of the user's eye. This makes a wearable computer a unique platform for mobile, personal, and ubiquitous computing applications. However, wearable computer applications require special design considerations. While a body of developer knowledge has been accumulated for desktop applications, there is comparatively less knowledge for the development of wearable computer applications. While developing wearable computer applications, such as this spatial cognition aid, insight into how wearable computers affect users and their activities would be welcome.

In this chapter, a conceptual model for wearable computing applications is presented. This model describes a wearable computer as a mediator of relationships between the user, other individuals, and the environment. This model may help define the design spaces available in wearable computing. It can also be a useful guide for developers of new wearable computer applications. This model can be suggest ways to develop a simple application idea into an application architecture. It can also help generate new variations and extensions for that application.

This chapter will describe the model in general and show how it can be used to classify current research projects and applications in wearable computing. Next will follow a demonstration of how the model can be used to suggest ways to develop a new application idea. Finally, the model will be used to outline the architecture of the spatial cognition aid under consideration in this dissertation. Later chapters in this dissertation will address the particular components of the spatial cognition aid's architecture.

3.2 Conceptual Models

In general, there are a number of reasons to devise a conceptual model for a particular design domain. These reasons may include:

- To suggest the structure and extent of a design space.
- To direct attention to portions of the domain that have not been addressed to satisfaction.
- To classify, compare, and relate existing work.
- To guide the design of a work in the domain.

A conceptual model can be a useful tool for understanding a particular domain. An example is Card et al's taxonomy that modeled the design space of input devices [21]. This allowed classification of previous devices and helped suggest new devices. Other conceptual models assist in developing the architecture of new applications. For example, the model-view-controller (MVC) paradigm of Smalltalk [73] or the presentation-abstraction-control (PAC) model [28] can help developers define the object classes and object hierarchy for interactive computer applications.

Ubiquitous computing also has some important conceptual models that have driven infrastructure and application development. A simple conceptual model underlies Hewlett-Packard's Cooltown [23, 12, 68, 67], a pervasive computing project that aims to strengthen the link between the real world and the virtual world of the web. The conceptual model identifies three entities: places, people, and things. Each entity is then provided with a "web presence", for example, things are given embedded web servers, people own web pages with links to communication services, and places are served by PlaceManagers that organize location based information and services.

Another example is the conceptual model embodied by Dey's Context Toolkit, an architecture for capturing and delivering contextual information [33]. In this model, contextual data is collected, processed, and delivered by five entity types: context widgets, interpreters, aggregators, services, and discoverers. This framework allows developers to write new components, reuse components, and connect them in various ways to support a wide variety of context aware applications.

These models from ubiquitous computing can inform certain aspects of wearable computing. The Context Toolkit provides useful abstractions for context aware aspects of wearable computing applications. The Cooltown project articulates ideas that may be useful to application designers who chose a web metaphor for their systems. For a more general view of wearable computing, it may be advantageous to consider another model that addresses the role of a wearable in the relationships of its user.

3.3 Wearable Computers as Relationship Mediators

Wearable computers fill a unique niche in human-computer interaction. They are carried by the user, are always on and available for input and output, and are exposed to the same experiences and environments that the user encounters. They are designed to be unobtrusive and avoid interfering with a user's activities. This close association allows wearable computers to participate in, and mediate, many of the relationships of the user. Accordingly, a conceptual model of wearable computing should focus on the relationships that are mediated by a wearable computer.

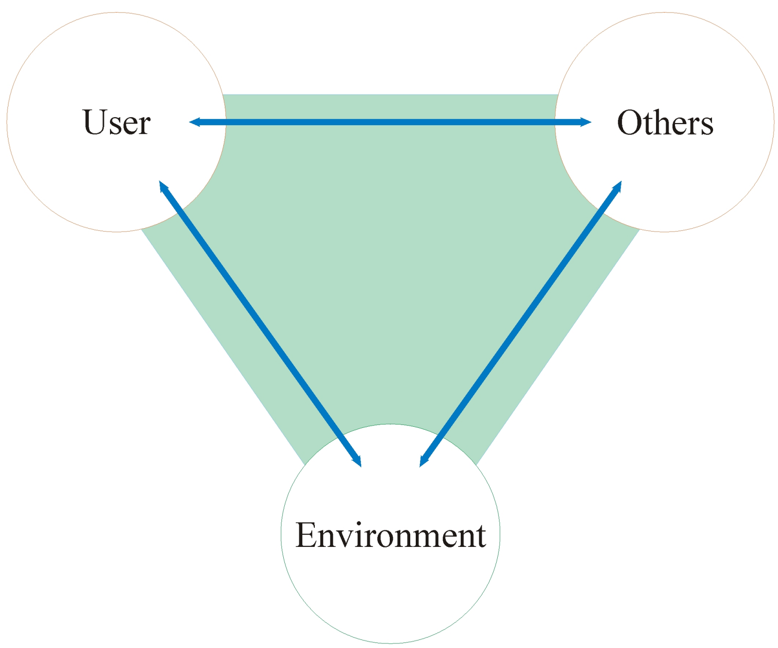


Figure 4: User have relationships with the environment and others.

The typical user will have relationships with two classes of entities. The first class consists of the environment. The second class consists of other individuals. Users perceive and react to the environment. They may survey their surroundings to avoid cars and other obstacles. They may look for tools and other items, and then use those tools to accomplish particular tasks. They may also plan routes and travel through the environment. The relationships with other individuals can also be complex and varied. Individuals communicate, work together, share information, play, and even conflict. They may be in the same room at the same time, or be separated by time and/or distance.

We can represent these relationships with arcs between the different entities (Figure 4). The addition of a wearable computer changes these relationships since these relationships can be mediated by the wearable computer. For example, wearable computers can automatically exchange contact information when two people meet for the first time. This changes the social relationship between the user and other individual by replacing the formal ceremony (in some societies) of business card exchange. This mediation is represented as an arc passing through the wearable computer's sphere of influence.

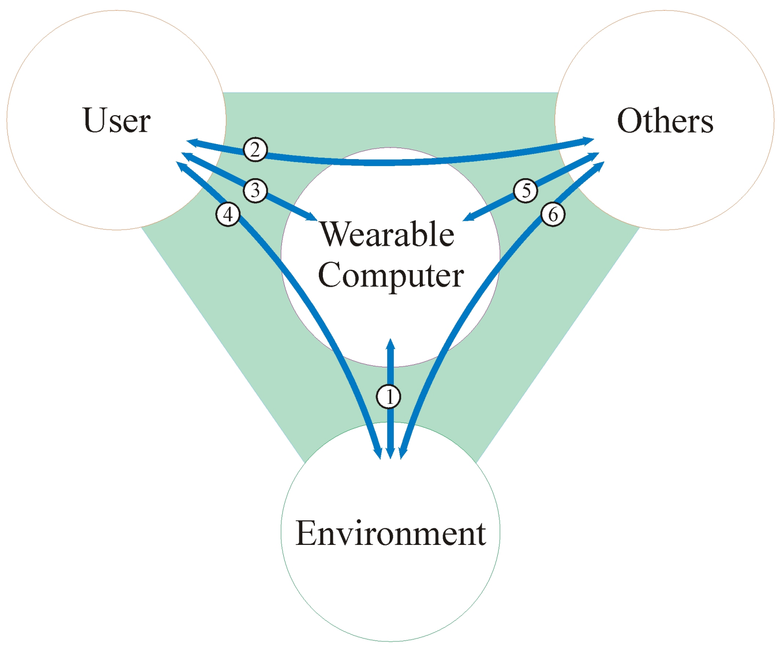


Figure 5: The addition of a wearable computer which can mediates various user relationships.

The addition of the wearable computer also establishes new relationships with the pre-existing entities (Figure 5). For example, the wearable may autonomously gather information from the

Table 1: A list of the relationships involving the user and the wearable computer.

1	Wearable Computer to Environment
2	User to Others (Mediated by the Wearable Computer)
3	User to Wearable Computer
4	User to Environment (Mediated by the Wearable Computer)
5	Others to Wearable Computer
6	Others to Environment (Mediated by the Wearable Computer)

environment through its own set of sensors, which creates a new relationship between the wearable and the environment. With the addition of these new relationships, there are a total of six different relationship arcs in this new diagram (Table 1).

This new diagram illustrates the basic relationship mediation model. However, it is important to also characterize each of these relationships arcs. The following subsections will describe these relationships in detail. Also, examples from various research projects will be discussed, showing how the model can be used to classify these projects.

3.3.1 Wearable Computer to Environment

Wearable computers often must be cognizant of the environment. They may be required to collect information about the environment in order to inform the user or help the user perform a task. The model shows no participation of the user in this relationship, so this refers to any environmental data collection that is largely autonomous.

One of the most common environmental information requirements is location awareness. The number of mobile computing, wearable computing, and augmented reality applications that have utilized location awareness are too numerous to list. However, some notable developments in location sensing are listed below. Hightower and Borriello [52] also provide a survey of location systems.

- The early use of bar codes for wearable computer location [133].
- The use of GPS for location aware applications [1].

- Fusing data from multiple sensors for determining location and orientation [5, 167].

- The use of computer vision to determine location, especially without the use of specialized fudicial marks [139, 121, 25].

- Inexpensive beacon systems (infrared, radio frequency, sonic, etc.) for determining location [161, 160, 138, 110, 113, 22].

Location is not the only type of environmental information that can be collected. Various sensors can be used to capture information such as video, audio, temperature, etc. Other sensors such as IR sensors, RF tag readers, computer vision enabled cameras, or bar code readers can access information in the environment from beacons or tags. Computer vision algorithms can also be used by the wearable to identify untagged objects in the environment. In the DyPERS (Dynamic Personal Enhanced Reality System) project, a wearable computer was built to visually recognize paintings in a art gallery environment and present additional background information about the artist and the style of the painting [125].

Wearable computers can also gather environmental information by tapping into sensor networks or databases of environmental information. Many of these geospatial databases are conceived as extensions of the World Wide Web. One example is the WorldBoard [136], in which Spohrer described a system for mapping geographic coordinates to web pages on a web server. A specific location in the world would have an associated web page which could be accessed when visiting that location. In a similar vein, projects within Hewlett-Packard's Cooltown initiative have explored the use of various web servers, beacons, and tags to link web based information and services to objects and places [23, 12, 68, 67].

Another example is the Real World Wide Web [70], an augmented reality instantiation of the WorldBoard concept. The RWWW proposed the linking of web pages containing 2D or 3D visual and auditory data to contextual data for location, activities, or persons. The RWWW browser consisted of a 3D augmented reality system for a wearable computer. Information would be retrieved and displayed in 3D around the user according to the user's context.

With these sensor networks and databases of environmental information, it is also possible that the wearable can reverse the previously described relationship. That is, rather than receiving information from the environment, it transmits information about the environment. For example, the wearable can write information into an environmental information database or participate as a sensor platform in a sensor network. A community of wearable computers may provide data on the temperature and humidity in various rooms of a building. Other wearable computers, worn by automobile commuters, can provide information about traffic and congestion in a freeway system. Another reverse relationship would be opportunistic annexation, as discussed by Pierce and Mahaney [109]. Wearable computers could automatically detect and employ computing resources in the near environment, such as large displays, printers, audio systems, or even processors.

3.3.2 User to Others, Mediated by a Wearable Computer

Wearable computer users often need to communicate, collaborate, and relate to others. Developers should consider a wide range of possible roles assumed by others. For example, the other individuals may be collaborating with the user towards a particular goal, competing, conflicting, or merely bystanding. Variations in technology usage may have the others using similar wearable computers, dissimilar devices (perhaps PDA's or desktops), or no computing technology at all. For the purposes of the relationship mediation model, the technology is grouped with the other individual as in Figure 6.

The developer should be able to design for user relationships with other individuals who are quite different than the wearable computer user. In fact, the other individual may not be human, but may instead be a dog [123]! Furthermore, the designer should consider different types of relationships. As in other CSCW applications, the relationship may be local or remote. It may also occur at the same time, or at different times (synchronous or asynchronous).

Kortuem and others have been conducting an ongoing research program in social relationships mediated by wearable computers [71, 72]. They have proposed the idea of "Wearable Community" in which wearable computers act as agents on behalf of their users. The wearables would augment the same time, same place, "in the flesh" social encounters. For example, their Genie application allows a user to compile a list of pressing questions. When two wearable users meet, the wearables trade questions, and the other user can decide if they have the expertise or willingness to converse

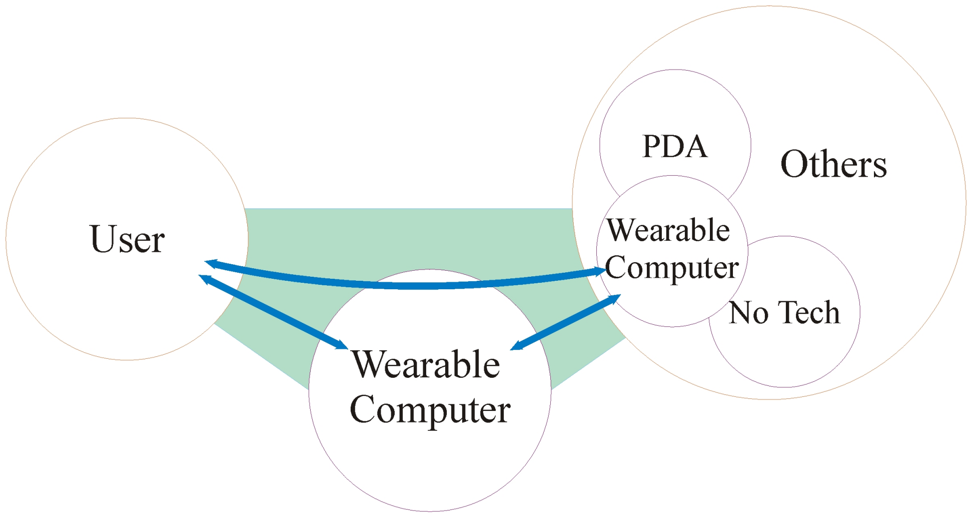


Figure 6: Users relate to others who may employ various technologies

about the questions. This brings up a new conversation topic of shared interest, or possibly identifies an expert who may have the answer that the user has sought for some time. They have also suggested applications for task trading (you pick up my laundry and I'll pick up your groceries), exchanging music playlists, and several other social interactions.

A wearable computer can also be used to recognize faces and determine when others approach for conversation [132]. This gives the wearable an opportunity to retrieve and present stored information about the conversant, such as identity or previous topics of conversation. Another interpersonal relationship is seen in medical monitoring systems. A doctor can use a wearable to monitor the vital signs of patients [99].

Various communication paradigms can be also supported. Wearables can provide translation, for example, sign language to spoken language [20]. Wearable computers can facilitate remote communication of both synchronous and asynchronous nature. Wearable computers easily support email and instant messaging services. Wearables can also provide video and audio streaming. For example, a wearable was used in collaborative maintenance tasks with supervisors providing real-time advice to field workers [14]. Some wearable computer applications have been designed to support group messaging [91] and presence awareness [164]. A modern variation on the idea of calling cards can be implemented by allowing wearable users to leave messages at a particular location [116].

3.3.3 User to Wearable Computer

This relationship describes the input/output channel between the user and the wearable. This relationship is perhaps the most straight forward and immediate in the model. This relationship includes the hardware used by the wearable to present information to the user, for example, eyeglass mounted displays, headphones, and tactile transducers. It also includes aspects of interface and information presentation, for example computer screen layout, widgets used in a graphical interface, sound mappings and audio design, or the selection of tactile sensations.

Wearable computers have often used head mounted visual displays manufactured by companies such as Sony, MicroOptical, Via, Liteeye, and others. However, researchers continue to development and evaluate new forms of head mounted displays [134, 81, 64], including virtual retinal displays [153]. Development of output modalities, such as audio [124], and tactile displays [118, 154] also continues.

The user to wearable computer relationship also describes how users provide input to the wearable. This may be through explicit commands, as through chording keyboard, voice, or gesture commands. It may also include non-explicit input, where a wearable computer uses sensors and/or pattern recognition to perceive user activity that may not be specifically directed towards the wearable. One example would be the logging of the user's medical data such as respiration and heart rate. Another example would be using accelerometers to determine whether the user is walking, sitting, or using a particular tool [76, 114]. A large percentage of wearable computer conference papers are descriptions, demonstrations, and evaluations of novel input devices and novel interaction techniques.

3.3.4 User to Environment, Mediated by a Wearable Computer

Individuals will perceive the environment around them whether they have a wearable computer or not. However, wearable computers will likely change how they perceive that environment. Any form of wearable computer output (visual, auditory, or tactile) can partially mask the user's perception of the environment or direct the user's attention away from the environment. The wearable can also mediate the user's perception of the environment in a purposeful way.

An excellent example of a wearable computer system that mediates a user's perception of the environment are wearable augmented reality systems. In such systems, like Columbia's Mobile Augmented Reality System (MARS) [41], virtual information is overlaid on the user's view of the environment. Another approach is a system that removes environmental data, for example replacing or masking out advertising and other signs [86]. Other researchers have been able to enhance vision or map visual information to other senses for the visually impaired [51, 111, 38].

Map navigation systems also provide a mediated reality by providing map information and enhanced direction and self-location abilities. Some wearables also act as surveying aids, allowing users to capture the geometry of roads, buildings, and other geographic features [107, 7]. These aids also enhance a user's perception of the environment.

It is also possible to develop wearable computers that help users manipulate their environments. A television or lighting remote control is a very simple environmental manipulation tool. Wearables can provide remote interfaces for people with disabilities [119]. Since disabilities can vary greatly, a personalized wearable interface can provide better access to public devices such as ATMs, information kiosks, etc.

3.3.5 Others to Wearable Computer

There are times when other individuals may wish to access information or services on someone else's wearable computer. At first glance, this relationship may appear similar to the relationship between the user and others. However, the relationship between a user and the other individual is characterized by the direct participation of the user. In the relationship between others and the wearable, the user is not a direct participant.

This relationship can be any interchange of information about the user, or information about the wearable that is instigated by the wearable computer. An example of this type of relationship could be a co-worker accessing a web page that is generated by the wearable computer. The web page could show the current status of the wearable computer, for example, uptime, battery level, etc. Automatic location sharing would also be an example of this relationship. Privacy (user control of information) can be an issue since the other individuals may be family, or close friends, co-workers, or strangers. Even bystanders may overhear a wearable computer's auditory interface and inadvertently join this relationship.

Furthermore, this relationship may be reciprocal. A wearable computer that senses other individuals and records their image or activity has also brought a bystanding individual into the relationship. What awareness, input, and control does the bystander have in this relationship?

Privacy is a fundamental concern in this relationship, regardless of direction. This may arise due to the wearable's privileged position and its covert nature which can create potential asymmetries in information sharing. This is not to say that issues of privacy do not arise elsewhere in the overall model. (Perhaps a user would sometimes want privacy from their own wearable?) Since privacy is a concern, critical dimensions of this relationship including the type of information that is available, who can access that information, how that information can be accessed, when and where that access is allowed, and how much awareness is given to the humans in this interchange. Recent discussion and projects that address privacy in ubiquitous computing environments include Palen and Dourish [102], Jiang et al [59], and Langheinrich [77].

3.3.6 Others to Environment, Mediated by Wearable Computer

Other individuals may gather information about the environment from someone else's wearable computer. These individuals may wish to perceive the environment as mediated by another person's wearable. This is very similar to the previously described relationship between wearable computer and other individuals. However, the focus here is on environmental information.

This information may consist of live sensor feeds, such as video or audio, or other information, such as temperature, pressure, and other meteorological data. Again, privacy can be a concern. Some data, such as meteorological, can be reasonably anonymous, although tight coupling with location data may greatly reduce anonymity. Likewise, audio and video can raise privacy concerns since they may reveal identity and activity.

In an early example of a wearable computer providing and mediating access between others and the environment, Mann used a wearable to compile photographic logs which were made available on his web site [87]. Maintenance tasks are another situation where it is often useful for remote collaborators to perceive the environment through a fieldworker's wearable computer. For example, in the Netman project [14], video and audio was delivered from the wearable of a field worker back to a supervisor in an office. The supervisor could provide expert assistance to the fieldworker as they performed computer network maintenance tasks. They termed this remote access to wearable computer sensors as "remote sensing".

Other individuals can be given direct access to the wearable's sensors, in other words, access to "raw" data. Another possibility is access to environmental data that is processed to a degree. The Eyetap device, used in conjunction with a gyroscopic head tracker, was used to stitch together an image, an environmental map, of the user's surroundings. Other Eyetap users, also using a head tracker, can view this environmental map as if they were present in the other user's environment [148].

The direction of the relationship can also be reversed. The other individual can modify the user's environment through the wearable computer. For example, with Telepointer [88], a remote collaborator could control a servo controlled laser pointer on a wearable, illuminating objects of interest in the wearable user's environment. Bauer et al also proposed the possibility of "remote manipulation" as a collaboration technique for wearables [14]. One could imagine manipulator arms on a wearable for moving objects or remote control capabilities.

3.4 A Design Process with Variations on a Theme

In a fugue, a musical composition form, a single musical theme is presented. However, a creative composer can devise intricate variations and permutations on the theme, preventing the work from becoming dull and uninteresting. By considering the relationship mediation model, applications for wearable computing can be developed in the same manner. A single application idea can be spun out into a full design with a variety of extensions and variations. The following steps will demonstrate such a process.

3.4.1 Articulate the Application

Wearable computer applications should first be articulated in human-centric terms. For example, a classic wearable computer application is augmenting or assisting human memory. It is important to note that concepts like context sensing, face recognition, or mobile input devices are not fully formed applications, but rather wearable computer functions or abilities. These abilities may serve an application such as augmenting memory, but are not an end in and of themselves.

3.4.2 Identify the Primary Relationships

Next, the application designer should identify the primary relationships involved in providing a solution to the application. For many applications, this may simply be an input/output channel between the user and the wearable computer.

To carry the augmenting human memory example further, developers of the Remembrance Agent [117] used a head mounted display and a Twiddler chording keyboard to provide this I/O channel. A user would type notes during conversations or lectures. The software agent would examine the notes, find matches with older documents and notes, and suggest related materials. In effect, it acted as a peripheral associative memory. During conversations or class lectures, the Remembrance Agent could bring up related conference papers. These documents might provide answers to questions the user was asked. With a user who took diligent notes, it could remind the user about the content of previous conversations with particular individuals, even if years had passed between meetings.

3.4.3 Extend to Other Relationships

The designer should then examine the different relationships in the model and imagine ways to that their system could participate in these relationships. To their credit, the designers of the Remembrance Agent developed their system along many of these lines. For example, two or more users of the Remembrance Agent could synchronize their databases, in effect sharing memories. This extends the application into the user to others relationship, since it requires action on the part of both the user and the other individual. However, if database sharing is autonomous, it becomes a wearable to others relationship. For example, the wearable can make the Remembrance Agent database available to anyone, but only while they are in the same room. It would then be advantageous to be an “information groupie,” basking in the presence of a group of wearable users with a diverse set of knowledge in their databases.

The application participates in another relationship if the wearable is allowed to gather information from the environment. There are many ways that location sensing could be used. Notes could be assigned creation locations and access locations, saving more contextual data for relevance matching. Perhaps notes could also be “stored” at a particular location in the environment. As wearable computer users enter new rooms, new documents, such as maintenance procedures, operation manuals, and maps could be made available through a location based database. These documents could also be accessed by the Remembrance Agent, “reminding” the user how to find an office, operate a fax machine, or repair machinery in that building.

The wearable could also change the way the user perceives the environment with an augmented reality approach. Perhaps documents, such as reminder notes, could be displayed over particular objects, like a refrigerator or telephone [139]. The Remembrance Agent could mediate the environment for other individuals. For example, another individual could examine an object belonging to the wearable user. The wearable could detect which object was being handled (perhaps with distributed sensors) and transmit or playback personal history or other information relating to that object.

3.4.4 Vary the Participation in the Relationships

It is important to brainstorm multiple ways for the application to participate in the different relationships. Perhaps not every idea will be feasible, but it is a good design practice to generate multiple ideas and cull later. These ideas can be prototyped and evaluated later.

It is often easy to consider changes in input and output devices. For example, the Remembrance Agent could rely on speech recognition. Perhaps a whispered reminder in the ear could be an interesting output technique. A tactile transducer in a ring could be analogous to a string tied around a finger.

Designers should consider different social scenarios when developing alternative ways for the wearable to participate in the user to others relationship. Perhaps consider who initiates a conversation or who gets information first. For example, the Remembrance Agent could broadcast its current search to all nearby wearables. Agents on other wearables could examine their document databases and return possible matches to the first agent. Depending on which user is notified, either the first user could approach other individuals, asking for the unique related documents, or the other individuals could approach the first user, offering a helpful document. Asking for a favor, or offering a favor provides quite different social experiences.

For the wearable to environment relationship, developers should examine a number of sensors and sensing techniques for gathering environmental information. The data from a variety of inexpensive sensors can also be fused to provide better results. Various location systems can be employed. Wireless access to a database of environmental information can also provide rich and dynamic possibilities.

Since wearables have often been primarily designed to interact with a single user, it can be difficult to come up with ways for the wearable to interact with non-wearing others. Consider the wearable as a separate entity from the user, as is shown in the model diagram. This can help a designer imagine scenarios where wearables relate to non-wearers. For example, individuals look at each other for non-verbal feedback. This feedback can let people know emotional states, attention levels, and mental states such as consideration or deep thought. It may be useful for a wearable to provide feedback to others about its thinking process. This can allow others to determine if the user recalled the answer to a question, or if the Remembrance Agent suggested the answer. In some social situations, it may be useful to know the difference (see [141] for an anecdote about wearable use during examinations).

3.5 An Architecture for Spatial Cognition

In my research, I have explored the idea of a wearable computer based spatial cognition aid. The relationship mediation model has helped identify the required relationships and necessary components for a complete system for spatial cognition assistance. At a minimum, a spatial cognition aid must gather information about the user's environment, allow the user to interact with the data to study and explore it, and present the data to the user in order to enhance the user's perception of the environment. As such, the spatial cognition aid should participate in these relationships:

- Wearable to Environment
- User to Wearable Computer
- User to Environment (Mediated by Wearable Computer)

It is possible to include other relationships. For example, it would be interesting to allow a group of users to share their notes and annotations of the environment. This could allow the users to build up a group mental model of the environment. This would extend the spatial cognition aid into a user to others relationship. However, such additional features and relationships are not necessary for a basic spatial cognition aid. Accordingly, my research has focused on the three listed relationships. The following subsections discuss these relationships and components. In each of these areas, the research strategy has been to define several alternatives, build prototypes, and evaluate. Further details are available in the following chapters.

3.5.1 Wearable to Environment

In a spatial cognition aid, the wearable computer must inform the user about the structure of the surrounding environment. The wearable computer must therefore gather information about the environment. A GPS and an orientation sensor can be used to gather information about location and orientation. However, geographic information is also required to present a map to the user. A complete spatial cognition system should provide a source of geographic data.

A wearable computer can simply carry a set of data for the areas where the user will be traveling. This is the strategy used by most of my experiments with spatial cognition. It is satisfactory for most evaluation and research purposes. However, these data sets can go out of date. Users may also travel to new areas, requiring new data sets. Dynamic data, such as the locations of other individuals, are not available. A better solution would be to provide a geographic information server. Wearables can then download data over a wireless network as needed.

However, the basic server solution will face scalability problems. First, a large number of wearable computer users could overwhelm the server with numerous fetch requests. Second, users will potentially be distributed all over the globe, causing long lag times and slow transfer rates for users who are located far from the servers. Third, geographic information can be an extremely large and diverse set of data. For example, users may wish to see meteorological data, terrain data, building occupancy data, or locations of other individuals. Some of this data may change quite rapidly. A small number of servers, or a single schema will have difficulty handling all of the environmental information.

To meet these concerns, I have designed a scalable system of geographically distributed servers where location servers index a variety of geographic data servers. I have used prototypes of this system to provide information, such as meteorological data and locations of persons, to wearable computer applications.

3.5.2 User to Wearable Computer

In my prototypes, I have used a terrain visualization to allow users to see the layout of the surrounding environment. This terrain visualization presents detailed map-like images that are built from aerial imagery, 3D buildings, and elevation data. These images have been presented to the users on an eyeglass mounted display. While there are some issues with display brightness and mechanical mounting, this appears to be a relatively effective output channel.

However, there is also a need for user input to the system. A user may be able to develop a better understanding of the terrain if they can navigate and explore the visualization. While the GPS will center the map around the user's location, the user may wish to preview an area before they arrive. Sometimes a user will wish to zoom in for more detail or zoom out for an overall view. These activities require navigation and an effective user interface. However, traditional computer interfaces, such as keyboard and mouse, prove to be unsatisfactory for a number of reasons.

To fill this need for navigation input, I have identified and examined several candidate interfaces for navigation tasks. These candidates employed multimodal speech and gesture recognition as well as two handed interaction. I conducted several experiments to determine which candidate interfaces were most effective for users navigating inside their terrain visualizations.

3.5.3 User to Environment (Mediated by the Wearable Computer)

With the previously mention components, it is possible to create a wearable computer based visualization and populate it with information received from a system of data servers. It is also possible to provide interaction techniques to allow the user to navigate through that visualization. However, it remains to be seen whether such a visualization can improve an individual's understanding of the environment. Furthermore, how can that visualization be presented to the user in a way that best compliments the user's perception of the environment?

The key relationship in a spatial cognition aid is the mediation of the user's perception of the environment. The wearable computer must present a view of the environment to the user that is well integrated, easy to understand, and provides the user with a better awareness of the environment's structure.

Towards this end, I have conducted a series of experiments to test a variety of map information presentations. These experiments have shown how the wearable computer should present information to the user. They have also shown that the wearable computer can indeed augment a user's spatial cognition and improve a user's mental map.

3.6 Summary

This chapter introduced a conceptual model for wearable computer applications. The model is based on the notion that wearable computers can mediate the relationships of the user. The relationship mediation model identifies these relationships and describes how wearable computers can participate in the relationships.

This model can classify previous work and suggest ways to develop ideas into new application and create extensions and variations on the application's architecture. The model was used to provide an architectural outline of the spatial cognition aid under consideration in this dissertation. The following chapters of this dissertation will describe these components in detail.

In considering a conceptual model, it is useful to reflect on the advice of Statistician George Box, who wrote, "All models are wrong but some are useful." [19] This relationship mediation model can be one starting point for discussions about useful models and useful design guidelines in wearable computing. Capturing and disseminating design concepts and practices will become increasingly important as the field of wearable computing develops and matures. The participation of the wearable community, researchers, developers, and other stakeholders is vital in this process.

CHAPTER IV

A SERVER INFRASTRUCTURE FOR SPATIAL INFORMATION

4.1 Introduction

Wearable computer applications often must gather information about the user's surrounding environment. The wearable can employ various onboard sensors. A spatial cognition aid can employ location sensors such as a GPS unit, and orientation sensors to determine user location and direction. However, spatial cognition aids must present information about the layout of the surrounding environment. The wearable must access a data source to get data concerning the nearby terrain, the locations and shapes of buildings, roads, etc. There are other mobile and wearable computing applications that need to gather environmental information. For example, navigation guides may need map and route information. Tourist guides need to gather background information about historic or scenic areas.

Many of these mobile and wearable computers applications, especially research prototypes and demonstrations, simply draw their data from files or a database in the computer's local data storage. This is quite sufficient for evaluations and demonstrations. However, for real applications, this approach is lacking. The environmental data can go out of date. The user may also wish to access data about locations that are outside the area covered by the computer's data.

Mobile or wearable computers could gather data from a server over a wireless network. However, server scalability can quickly become an issue. Large number of client requests can overwhelm a server. Users may be distributed around the world, causing severe lag and slow transfer rates for individuals who are located far from a server. Furthermore, there may be scalability challenges in handling the variety and amount of environmental data that can be made available. For example, there may be applications that require meteorological data, tourist information, traffic alerts, maps, locations of individuals, etc. The rights to these various datasets may be owned and controlled by different entities. The datasets may also be quite large. It would be difficult to organize these various datasets into a single system. It is best to divide data, by location and type, among different servers. In this chapter, I describe a geographically distributed system of location servers that index into data servers of various types. This system is a loose confederation of servers that easily allows data servers to join the system. This system divides both indexing and data geographically, allowing it to scale to handle larger numbers of both users and data servers.

This infrastructure was briefly mentioned in a VRST 2001 paper [75], and further discussed in a paper at the 2003 Young Investigator's Forum in VR [74]. However, a full length description has not been previously available.

4.2 Related Work

Others have recognized the need to provide location based information and services. One approach is to provide a way to associate web pages with different geographic coordinates. This is the approach that Spohrer described in the WorldBoard [136]. Such systems can be described as geographic data lookup systems. They provide an index from location to data, i.e. they map location to particular pages on a single web server. However, such data lookup systems do not facilitate division of data between multiple, geographically distributed servers. Also, network traffic will have little geographic localization. The solution is to provide servers that index location to a group of servers. This arrangement is a geographic server lookup system. This system maps a location or region to a group of data servers.

Rover [9, 10] is another project that describes a framework for the distribution of location based information. In the Rover framework, there are five types of servers:

- Rover Controller: This provides central management of the rover services. It schedules and filters content according to client location and profile.

- Location Server: This is a service that helps clients determine their position. This could be replaced with an external location system like GPS.

- Media Streaming Unit: This is a server that streams audio or video to clients.

- Rover Database: This is a database that is used to store the state of clients as well as all content that is to be delivered to clients.

- Logger: Collects log messages from the instrumentation modules of each Rover server.

Rover is designed to provide basic data services like text, graphics, audio and video as well as transactional services that have commit semantics. These would include database transactions as in E-commerce or banking.

The Rover project has focused on system scalability by developing an “action model” for server processing. The researchers felt that server processing would be a scalability issue. Most server processing is thread based, perhaps assigning an individual thread to process a user’s requests, or a separate thread for each server operation. Scaling to large numbers of clients would create large numbers of threads that will experience large overheads for switching. Instead, the researchers developed the notion of actions based processing. Actions are small units of code that have no intervening I/O operations. Thus, execution time for an action can be bounded. Client requests are broken into various actions which can be scheduled very efficiently. The scalable server infrastructure described in this chapter seeks scalability by partitioning the information and the clients to be served according to geographical regions or domains. While actions may be useful for server scalability, geographic partitioning is also an important scaling mechanism. Rover has the concept of a domain, but it describes an administrative division. Each domain is a controller and the set of servers it manages. There is no explicit division of regions into information domains and no general methods to discover services available in a region and seamlessly switch to other domains as the user moves.

Rover also assigns the task of data filtering and personalization to the Rover controller. This is a centralized approach that can be a bottleneck for scalability and integration of new data types. Each data server will have to adapt to the filtering protocols of the central controller. The controller will have to be cognizant of each type of data that the system can serve. A more adaptable system is realized by allocating filtering to the individual data servers. This is seen with the inclusion of a separate media streaming server in the Rover system. Filtering and compression choices are highly dependent on the media type. It is best to leave such choices to server developers who know techniques for managing specific types of data and how those data will be utilized.

Nexus is another distribution infrastructure for location based information [55, 42, 95, 43]. The development priorities of Nexus reveal characteristics common to Geographic Information Systems

(GIS). One priority is the Augmented World Model (AWM) which presents a single, unified information model to applications. Since the data that forms the AWM comes from multiple sources, one priority of the Nexus project has been to properly conflate (fuse) different data sets. These data sources may conflict or be misaligned. A single, or unified, data representation of the world is desired.

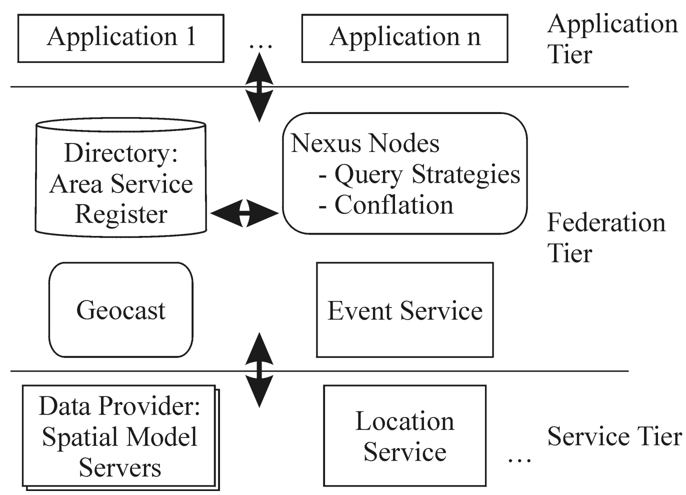


Figure 7: The architecture of Nexus, another system for distributing location based information.

Nexus is comprised of three layers (see Figure 7, based on a diagram by Fritsch and Volz [43]). The first layer is the application tier which consists of applications running on mobile clients. These applications communicate with the federation tier which handles queries from the applications and distributes requests to the appropriate data servers in the service tier. The data servers of the service tier store location information of clients and also the location based information such as spatial models of the environment. Here are descriptions of specific components in each tier:

- Nexus Node: Applications pass requests to the Nexus node which direct the request to the appropriate spatial model servers or Location Service. The Nexus node is part of the federation tier.

- Location Service: The location service, a service tier component, stores and retrieves the position of users.

- Spatial Model Servers: These service tier components manage static spatial data such as the layout of roads, and building locations.

- Area Service Register: This federation component contains meta data concerning the data sets available in the spatial model servers. The Nexus node consults the Area Service Register to determine how to direct queries from clients.

- Event Service: The event service notifies users when they enter predefined contexts. For example, a user can register to be informed of any sales when they pass by a store. This service is also part of the federation layer.

- Geocast Service: This federation tier service allows messages to be sent to all users in a region. This allows wide spread traffic alerts and similar emergency messages.

In Nexus, the federation layer routes application queries and returns data. This centralized approach can be advantageous for providing a uniform interface between applications and the information system. However, the server infrastructure described in this chapter provides a looser association between spatial information sources. This allows new data types and applications to be easily integrated into the system. The server infrastructure provides an indexing of available location based services rather than managing access to these data services and requiring specific interfaces. As location based services are just beginning to emerge, supporting innovation and change is more important than premature standardization.

4.3 Architecture

There are three parts to this system: clients, location servers, and data servers. The clients are users with the appropriate hardware, software, and networking access to participate in the system. These clients wish to access information about particular geographic regions. The location servers provide an server address lookup service for the geographic regions. The data servers provide specialized information such as weather, traffic, public transit schedules, or building information.

This system is designed to take advantage of the information locality of both clients and servers. Clients typically are only interested in information for their current location and a relatively small surrounding region. They will wish to connect to data servers that are relatively nearby to minimize lag, and also contain data for the user's region of interest. A client can communicate this region of interest to a location server and receive an index of servers that provide various types of data for that area. Clients with special purpose applications could automatically connect and retrieve data from the appropriate server. Clients with general purpose information browsing applications could be allowed to browse across several of these servers and access different types of data.

This system differentiates itself from other mobile information infrastructures because both data and indexing functions are distributed geographically. Furthermore, it is a loose confederation of data servers, allowing servers to join easily. In fact, mobile and wearable computers can also join as data servers. This can be useful for systems with sensors or users who have gathered and interpreted data that they wish to share.

4.3.1 Clients

Clients first register their position information with a nearby location server. Users will always be referred to the closest location server, which ensures that each location server only keeps track of users in a particular area. Users also send a radius, describing an area for which they want information. The location server will return the IP addresses and positions of other users in that area and IP addresses for data servers with information for that area.

A user may initiate communication with any of the nearby users. They might also register their area of interest with one or more of the information servers. While a user is registered with an information server and continues to give occasional position updates, the information server will provide updates. Furthermore, if the user moves out of the region for which the current information server has data, the user could be referred to another information server.

Users can also register as data servers, since they may wish to share data on their mobile or wearable computer. For example these systems may have sensors that capture meteorological data. Another scenario could be that of forward observers in a military unit. The observers may use mobile or wearable computers to enter the position, identify, speed, and direction of various entities on a battlefield. Other friendly units may wish to see the observations that have been made for their own proximal region.

4.3.2 Location Servers

In some mobile computing systems, a location server is a service that informs a user or a device of their location. However, for the practical purposes of a system designer, many technologies for location are rather self contained, for example, a GPS device. The system designer does not need to provide any "location server" to help a user determine their location. Furthermore, there are a number of location determination technologies [52] and it would be inadvisable to include such technologies inside a mobile information infrastructure. In this system, location determination is considered external and the location servers do not participate in location determination. Instead, the location servers act as clearing houses for location information. They store and disseminate the locations of users and data servers.

Location servers act as the backbone of the system. These location servers are responsible for receiving and storing the locations of users and servers. They are also responsible for providing this location information to other users who wish to retrieve information from others. They present a geographic indexing function for users and data servers. In effect, they act as a geographic counterpart to the Internet Domain Name System (DNS) [93]. However, the DNS maps a server name to a particular Internet Protocol (IP) address. The location servers must map a geographic region to several users and servers.

Each location server is responsible for a particular domain, or region of the world. These domains do not need to be the same size since domains with greater populations could generate more requests. These domains can be aligned on latitude and longitude boundaries, or arranged as circular or hexagonal cells.

Location servers also maintain a list of all the other location servers. This allows a client to make an index request of any location server. If the requested region is not in the location server's domain, the client can be informed of the appropriate location server to contact. This will ensure that index requests are properly localized. Furthermore, this provides a general way to determine the client's local domain and the available services. A client will find the appropriate location server by contacting any location server it knows.

Sometimes a client will make an index request for a region that overlaps multiple domains. One solution would be to have the client communicate with multiple location servers in order to find the appropriate data servers. However, since a single location server is assigned to keep track of the user's location, it is best that clients communicate with only one location server. The location server should forward the index request to the appropriate neighboring location servers and pass the results back to the client. Since location servers will typically cover an area larger than the user's area of interest, these requests should be relatively infrequent.

Clients and data servers must update their positions and areas periodically with the location server. This prevents the accumulation of zombies, which are location entries on a location server that do not correspond to a client or data server that are currently online. Zombies can occur if a client registers their location, then drops offline without unregistering. If a client or data server does not update their registration, the location server could remove any stale registrations, ones that are perhaps fifteen minutes or half-hour old.

4.3.3 Data Servers

The system provides a loose confederation of data servers, allowing new servers to be easily added to the system. This decentralized philosophy is necessary since data servers may be owned and developed by various entities. Furthermore, some freedom is extended to developers in terms of the protocols and data formats. There are two main requirements. Data servers must register with the appropriate location server and communicate the area for which they have data. They must also respond to user requests based on user location and area of interest.

The data servers can provide handling for request forwarding and multiple region requests that is similar to the techniques employed by the location servers. Alternatively, data servers can simply allow location servers to identify the proper data servers to clients.

The typical relationship between the data servers and clients will be a subscription based. That is, clients will register their position and addressing information with the data server and periodically update the position. The data server will deliver information and provide updates as data changes or the user moves. Filtering based on device capabilities and preferences can be done by the data server.

4.4 Discussion

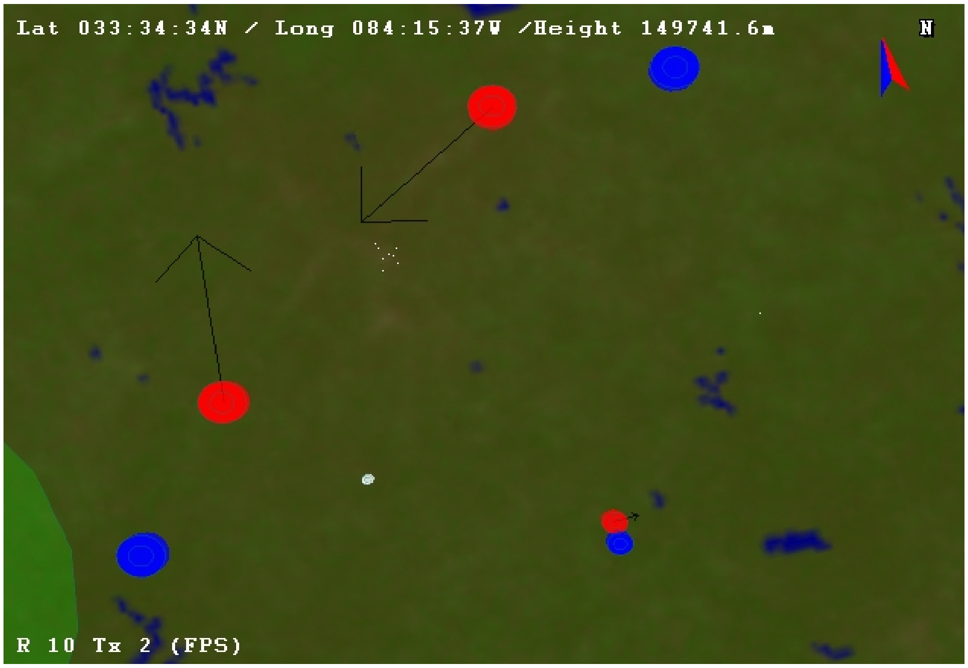


Figure 8: Mesocyclone data delivered by a prototype weather data server.

Various prototypes of data servers, client software, and location servers have been developed. A data server has been created to collect and distribute observations of moving entities made by forward observers. Another data server was built to distribute processed meteorological data from Doppler radar. Raw Doppler radar data was processed by algorithms to locate regions of wind shear. These regions, known as mesocyclones, can be indicators and precursors to severe weather phenomena such as thunderstorms and tornadoes. Figure 8 is a screen capture from a visualization of mesocyclones. This mesocyclone data was delivered by a prototype weather data server.

These prototypes have employed an 802.11b wireless network. With such a network, it is likely that particular clients will experience connectivity drop outs. These particular clients may reconnect with different IP addresses. To handle these situations, a simple UDP protocol was devised for registering clients with location servers. Clients and data servers are identified by unique hostname and username pairs. A hostname identifies a machine and a username identifies a human user. Each packet must be given unique name pairs so the location server can look up appropriate the IP address and port for sending responses.

Table 2: A simple UDP protocol for a location server prototype.

Packet Type	Data and Description
REGISTER	Hostname, Username, IP Address, Port Informs location server of location and address.
LOCATION	Hostname, Username, Latitude, Longitude, Radius Updates client location with the location server and acts as a keep alive. Data servers provide a radius to describe the area for which they have data.
SIGNOFF	Hostname, Username Inform location server that client or server will go offline.
QUERY	Hostname, Username, Radius An index request to receive nearby users and data servers.
ENTRY	Hostname, Username or Description, IP Address, Port, Latitude, Longitude Response from location server concerning nearby clients and data servers.
FORWARD	IP Address, Port If client is out of area, the client is directed to an appropriate location server.
PING	Hostname, Username, IP Address, Port Inquire if a location server is alive.
ALIVE	N/A Location server response to PING.

These prototypes were created to verify the data distribution aspects of the system. However, these prototypes have not addressed some issues in security and privacy. Those issues are recognized and can be addressed in future implementations.

The location servers and data servers in this system provide data that is tailored to the region that is requested by the user. Other types of filtering and customizing of data, perhaps according to device capabilities, is left to the implementers of the data servers. The output of the location servers is simple enough to not require any special filtering by device capabilities.

Security and privacy can also be concerns with this system. There are several ways that these concerns can be respected. Location servers could be configured to not share user locations with other users. They can also be extended to allow users to determine whether they wish to share their location, and with whom. Any transmission of location should also be made with the appropriate encryption. Unfortunately, it is not possible to entirely avoid transmission of user location. Location reporting by clients is necessary to retrieve the appropriate indexes from the location servers, or retrieve the appropriate information from the data servers. However, users could obscure their location by requesting data for a location that is randomly offset from their actual location. The user would also communicate a region of interest that is larger than normal, to cover their true region of interest. Care must be taken in choosing these random offsets and regions so that the true location can not be deduced by convergence over time. Another security issue is spoofing, or impersonation of a data server by an unauthorized entity. It is important to provide ways to verify and audit server identities.

4.5 Summary

In this chapter, a server infrastructure for distributing location based information was described. This infrastructure follows a philosophy of loose confederation and provides a lightweight framework. It divides location data among multiple, geographically distributed data servers. A similarly distributed set of location servers provides clients with an index of data servers for particular regions of interest. Client applications, run on mobile or wearable computers, can also act as data servers themselves. This infrastructure allows developers to design a variety of location based information services and easily integrate them into a world wide indexing system. Data filtering and personalization are left to the data servers themselves. System level management of these issues require tighter integration of these servers which can hinder the addition of new services. Since location based services are an emerging area, ease of entry is important to foster innovation.

To develop a spatial cognition aid that is not a research demonstration will require a general and flexible location based information infrastructure. A next generation spatial cognition aid must be able to gather map and other geographic layout information for any location. This infrastructure can serve that purpose. It serves as a key component of the wearable computer to environment relationship.

In the next chapter, the relationship between the user and the wearable computer will be explored. The scalable server infrastructure can provide environmental data to populate the spatial cognition aid. However, a user will need to navigate and interact with that environmental data. The following chapter describes various interaction techniques for navigation that can be used in a mobile, wearable computer setting.

CHAPTER V

MULTIMODAL AND TWO HANDED NAVIGATION

5.1 Introduction

Users must be able to interact with wearable computers. In a spatial cognition aid, users should be given the ability to interact with the model of the surrounding environment. This chapter will discuss some ways in which users can navigate inside the spatial cognition aid. Since traditional computer interfaces are not appropriate for wearable computers, I investigated and evaluated alternative interfaces. Two experiments were conducted. One examined navigation interfaces that were based on speech recognition, gesture recognition, and a combination of those two modes. A second experiment examined the various interfaces based on isometric joysticks and tilt sensors. These interfaces used a various two handed and one handed mappings for navigation.

The speech modality proved to be effective for the wearable computer environment, however interfaces based on gesture or speech and gesture proved to be less desirable. In the second experiment, a two handed interface with an aircraft metaphor proved to be effective. This chapter also shares some lessons for interface design that were derived from the experimental experience.

5.2 Background

A terrain visualization is an important component of a spatial cognition application on a wearable computer. This virtual model of the environment allows a variety of map-like views to be presented. Users can see the layout of the environment and perceive their location in relationship to other environmental features. Furthermore, it is also advantageous for spatial cognition applications as well as wayfinding applications if the user can peruse and explore the rest of the virtual model. This type of interaction requires navigation. However, there are some special challenges in this domain.

Navigation in a 3D visualization can be difficult. As in Wartell[163], concerns include the ability of users to manage seven degrees of freedom (three dimensions, three degrees of orientation, and scale) and the need for navigation methods to work at all spatial scales. Wartell also states that maintaining good stereo imagery can also be a concern. This is not applicable to the head mounted displays employed in the wearable computer system under consideration. However, with these head mounted displays, direct reference to the display, such as with pen tap or finger touch, is difficult. Thus, interaction modes and techniques requiring direct reference to the display should be avoided.

There are additional constraints imposed by wearable computing on input devices and the manner in which they can be used:

- Fatigue is important since the computer may be worn and used for long periods of time (perhaps 8 hours or more).
- Input devices must not require a desktop surface, like a typical mouse or keyboard [150].
- Input devices should be usable when the user is sitting, standing, or walking [45].
- The input devices must not be too encumbering. Hands free operation is best, but devices that can be easily and quickly engaged and disengaged may also be acceptable.
- Interaction should not distract the user from perceiving and dealing with the world; i.e. it should not make great demands of the user's attention or cognitive resources [13].

Two classes of candidate interfaces that could be used in wearable computer based visualizations were investigated and characterized. A speech and gesture based multimodal interface was the first interface to be considered. The second investigation examined one and two handed interfaces that employed isometric pointing devices and tilt sensors.

While these studies were conducted to explore interfaces for 3D wearable computer applications, they should also be of interest for ubiquitous computing environments of the future. These environments may be characterized by "walk up and use" applications on large screen displays. Users may wish to interact with these displays without donning special instruments and being tethered to a fixed location. Furthermore, users may be mobile and standing at a distance from the displays. This user mobility creates some of the same interaction constraints involved in wearable computing.

5.3 Multimodal Interaction

Multimodal interfaces are a promising alternative to tradition computer interfaces. Such interfaces use two or more input modalities, for example, speech and pen input, or speech and lip movement. For the wearable computer application under consideration, a multimodal interface using speech and hand gestures may be appropriate.

Speech is a rich channel for human-to-human communication and promises to be a rich channel for human-to-computer communication. Gestures can complement human speech in a number of ways. They may add redundancy and emphasis, or measures of quiet and privacy, humor, and description. Multimodal interfaces crafted from speech and gesture have greater expressive power, flexibility, and convenience.

Multimodal interfaces can experience a decreased error rate, as compared to the unimodal component interfaces. This is partly due to the freedom of the user to choose the means of expression. Since a large repertoire of expression is available, users will select and adapt to modes of expression that satisfy their preferences and minimize errors[101]. In noisy environments, the user can rely more on gesture or pen input. Such interfaces also accommodate users with different or changing capabilities. A user who is disabled or encumbered can use speech. Someone with a cold or an accent can employ more gesture or pen input. Multimodal interfaces also experience mutual disambiguation[100]. Recovery from some errors is possible because contextual information from the other input modes allows the system to correctly re-interpret the user's intentions.

Multimodal systems appear to be a good match for spatio-visual applications, such as visualization and virtual reality. Gestures allow concise spatial references and descriptions. Speech allows rich command and query interactions. While tracked gestures have been used to navigate and interact in virtual environments for some time, these usually involve cumbersome tethered devices and gloves that sense joint angles. In general, glove devices are cumbersome, imprecise in measuring hand orientation and posture[66]. Gloves are also unwieldy to share with other users. They wear out easily and can be uncomfortable. These, among other reasons, have led to work in vision based tracking devices for more natural interaction.

5.3.1 Related Work

There has been keen interest in multimodal control interfaces for a long period of time. Early work like Bolt's "Put That There" [18] has been followed by a large number of systems and studies. Some related work in multimodal interfaces for visualization environments is discussed below.

MSVT, the Multimodal Scientific Visualization Tool[60] is a semi-immersive visualization environment for exploring scientific data such as fluid flow simulations. The interface is composed of a pair of electro-magnetically tracked pinch gloves and voice recognition. Voice recognition provides over 20 commands and the gloves provide a variety of navigation, manipulation, and picking techniques. Visualization tools such as streamlines, rakes, and color planes are available. In our work we track hands without gloves, which encourages a more natural and unencumbered interaction. Furthermore, our visualization is a global terrain visualization with an extended range of scale, requiring richer navigation techniques.

Sharma et al.[127] describe another multimodal testbed composed of a virtual environment called MDScope and a graphical front-end called VMD. This system allows structural biologists to simulate the interaction of biomolecular structures. Interaction is through a simple command language composed of spoken actions executed with objects and parameters composed of both speech and gesture. The voice recognition system spots words from a continuous stream of speech while video streams from two fixed cameras are processed to yield 3D finger pointing and simple hand gestures. Our system uses a body mounted camera, so user mobility is enhanced.

BattleView[104] is a virtual reality battlefield application for supporting planning and decision making developed by the National Center for Supercomputing Applications. Much like the MDScope/VMD application, 3D pointing and simple hand gestures form the gesture part of the multimodal interface. IBM ViaVoice forms the speech recognition system. A multimodal integration module combines the recognizer streams. A state diagram describes the command language that allows users to navigate as well as select and manipulate virtual objects. Stereoscopic displays such as workbenches and single rear projected screens are supported. Again, a fixed single camera mounted on the display is used for gesture recognition, as opposed to a body mounted camera.

Quickset is a 2D map application with a rich pen and speech interface developed at the Oregon

Graduate Institute of Science and Technology[26]. Users can create and manipulate virtual entities on the map for a variety of applications, including medical informatics, military simulation and training, 3D terrain visualization, and disaster management. Quickset uses a 3 tier hierarchical recognition technique called Members-Teams-Committee. Member recognizers report results to one or more team leaders which apply various weighting schemes. These team leaders report to a committee which weights the results and provides a ranked list of multimedia interpretations. Each of these components is implemented as an agent that discover other components through a facilitator service. This allows the system to be flexible and robust towards errors.

Quickset has also been adapted to Dragon[61], a battlefield visualization tool developed at the Naval Research Laboratory[27]. Features of the VR system include “digital ink” that is deposited on the 3D terrain surface by raycasting. This ink plays the same role as pen strokes in 2D Quickset applications. Also, a 3D speech and 3D gesture vocabulary is integrated with the now available 3D information. An example would be the query “How high is this hill (3D gesture)?” Our multimodal interface is based on speech and hand gesture, rather than speech and pen stroke as in Quickset. Pen gestures require some reference or interaction with the display surface. With a body mounted camera, users can be distant from the display and still interact.

There is also some work in vision based gesture recognition interfaces for wearable computing. These include sign language interpretation [140, 20]. This area of work also includes the Gesture Pendant, a chest mounted camera for recognizing gestures. [137]. The Gesture Pendant hardware was used in the following study.

5.3.2 Method

This first study explored four interfaces for navigation in a 3D visualization. These interfaces include a mouse interface, a speech interface, a hand gesture interface, and a multimodal speech and gesture interface. The mouse interface was included as a baseline for comparison to help characterize the other interfaces. This study also attempted to determine the impact of each interface on cognitive load as well as take subjective measures such as discomfort and user preference.

5.3.2.1 Participants

Twenty-four students were recruited from an undergraduate computer game design course. The participants were male, and most had experience with 3D graphics in gaming or 3D design applications. Some had used commercially available speech recognition in the form of PC applications or telephone information systems. A small number had used applications with hand or arm gesture recognition. While not representative of the population in general, this group should be adaptable to new interfaces.

5.3.2.2 Apparatus

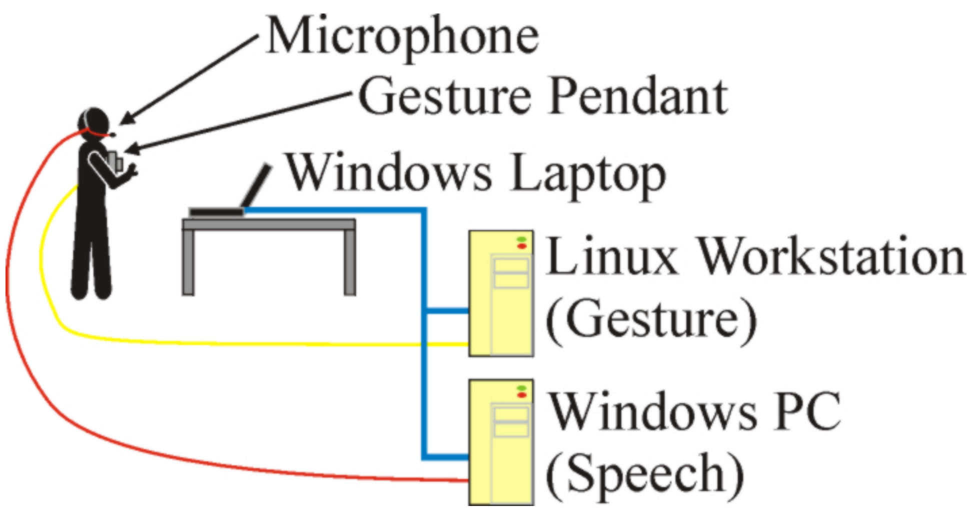


Figure 9: The interface architecture for the multimodal interface study

The apparatus used in this experiment consisted of a Pentium III 850MHz laptop running the VGIS visualization application. The visualization provided a top down view of the world for navigation. A Linux workstation ran vision algorithms for the gesture recognition interface and sent packets with the results over a network to the laptop. These algorithms segmented a video image and identified the user's hand. The location and motion of the hand's centroid was recognized and characterized to determine the gesture. A Windows NT system ran a speech recognition interface and also sent the results over a network to the laptop. A diagram of the system is in Figure 9. While a head mounted display could have been used to better reflect the configuration of a true wearable computer, the focus of the experiment was on user input and navigation. The display was not a primary concern. Avoiding a head mounted display also streamlined experimentation due to fitting issues with head mounted displays.

The following four candidate interfaces were evaluated:

Mouse Interface: The simplified mouse interface uses a three-button mouse. Clicking the left button and dragging allows the user to pan horizontally and vertically. Pressing the middle button zooms in and pressing the right button zooms out. An additional zoom characteristic was that the mouse position determined the center of the zoom in and zoom out motions. This allows users to pan a small amount while zooming, allowing fine adjustments of their trajectories.

Speech Interface: The speech interface uses Microsoft's Speech API for recognition. No user training is needed, but some users with certain US regional dialects or non-US accents experience more recognition difficulties. Fortunately, synonyms are available for commands that often cause difficulty.

The speech interface provides three classes of commands (Table 3). There are movement commands that start the user moving in a particular direction. For example, the user can "Move left" or "Move right" to pan horizontally. "Move up" and "Move down" are used to pan vertically. A second movement command stops the previous movement and begins a new motion. This constraint was added after initial testing when we found that combined movements proved more difficult for users to control. The speed control commands, "Faster", "Slower", and "Stop", allow the user to modify speed once a movement command has been given. The final class of commands, the discrete movement commands, "Jump left", "Jump up", "Jump down", are much like the movement commands, except the user moves in small jumps without control of speed.

Gesture Interface: The gesture interface uses the Gesture Pendant[4, 137]. It consists of a small, black and white, NTSC video camera that is worn on the user's chest (Figure 10). Since bare

Table 3: A sample of recognized speech commands for the speech based interface.

Movement Commands
Move {In, Out, Forwards, Backwards}
Move {Left, Right, Up, Down}
Move {Higher, Lower}
Speed Commands
Slower, Faster, Stop
Discrete Movement Commands
Jump {Forwards, Backwards}
Jump {Left, Right, Up, Down}
Jump {Higher, Lower}

human skin is very reflective to infrared light, regardless of skin tone, an array of infrared emitting LED's is used to illuminate the camera's field of view. An infrared filter over the camera's lens prevents other light sources from interfering with segmentation of the user's hand. The limited range of the LED's prevents objects beyond a few feet from being seen by the camera. With a wide angle lens on the camera, the Gesture Pendant yields a field of view about 20 inches wide by 15 inches in height at a one foot distance. At that distance, although there is some fisheye distortion, a single pixel of the 320x240 video image should subtend around 1/16 inch.

The recognized gestures are shown in Figure 11. Sweeping a vertical finger in a horizontal direction allows horizontal panning. Sweeping a horizontal finger from the right hand up and down allows vertical panning. Sweeping a horizontal finger from the left hand up and down allows the user to zoom in and zoom out. A flat palm facing the chest stops any motion. As in the speech interface, a second movement command stops any previous movement and begins a new motion.

Multimodal Interface: The multimodal interface uses both speech commands and gestures. The speech component is basically the same as the speech interface; but with gestures used for rate control. For example, the user first gives a speech command such as "Move left", which

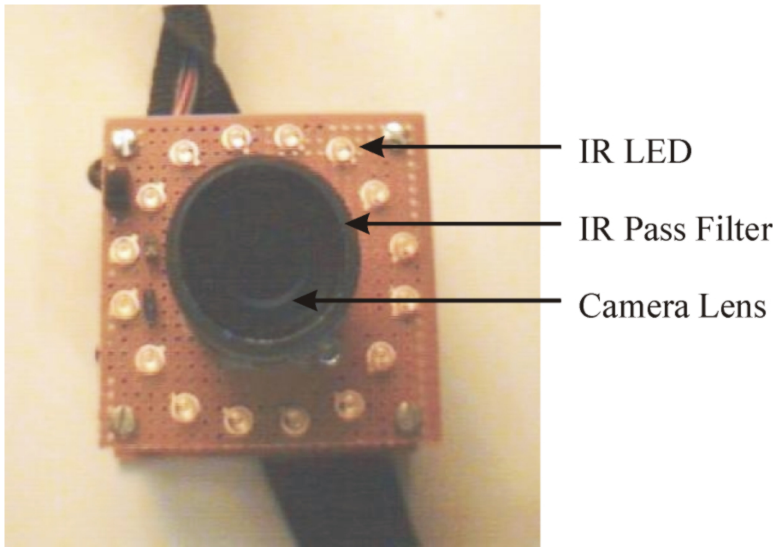


Figure 10: The Gesture Pendant, a chest mounted camera for vision based gesture recognition

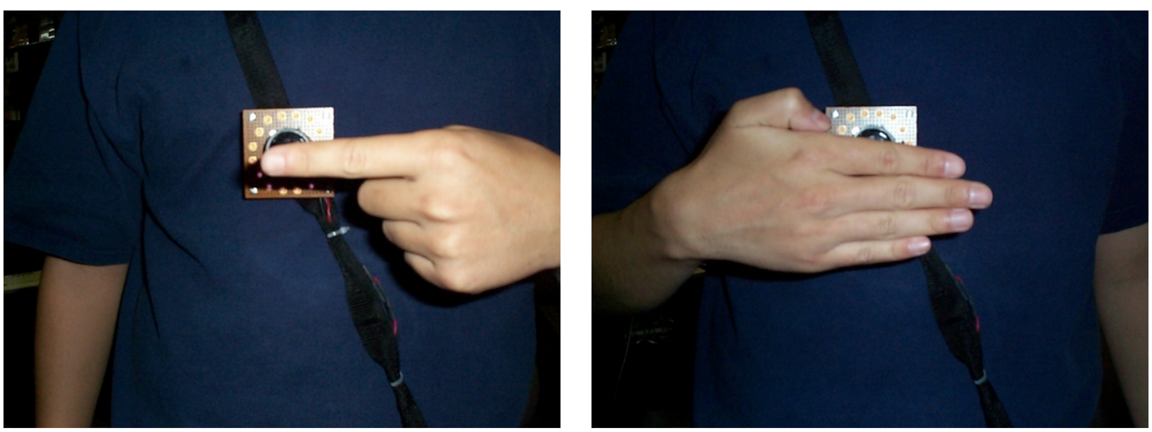
causes the motion in the left direction. The gesture component segments the user's finger tip and detects x and y motion of the finger tip. By moving the finger tip left and right, the user can speed, slow, or even slightly reverse the motion. Zooming and vertical panning are controlled by vertical displacement of a horizontal finger tip. Two additional speech commands were also added to provide alternative commands for a few functions. "Horizontal" allows the horizontal finger tip displacement to determine both the direction and speed of horizontal panning and "Vertical" allows vertical finger tip displacement to do the same for vertical panning.

5.3.2.3 Experimental Design

The experiment compared the effect of a single variable (interface type) on a variety of objective and subjective measures. This experiment used a "within subjects" design, meaning that each participant used each and every interface type. The interfaces were presented to each participant in a unique order to counter learning effects.

A single interface task consisted of navigating to four different targets. These targets were each associated with a unique symbol. This task was repeated, with different target symbols and

Moving the right index finger up and down causes vertical panning. Moving a vertical index finger left and right causes horizontal panning.



Moving the left index finger up and down causes zooming. An open palm stops movement.

Figure 11: Gestures recognized by the video based gesture recognition software.

locations, for each of the four interfaces. There were two objective measures taken. The time needed to reach each target was measured. Participants were also given a memory test to determine if they remembered the symbols they saw, where the symbols were located, and in what order the symbols were encountered. This memory test was a tool to assess the cognitive load of the interface. One widely used result of cognitive psychology shows that there are severe limitations on working memory capacity[92]. Furthermore, when individuals are forced to use working memory or other cognitive resources, information is lost or displaced[6]. The cognitive load of a particular interface should be reflected in the quantity of information that an individual can remember while using that interface.

After each interface task, participants were asked to rate the interface for ten specific interface characteristics on five point disagree-agree response scales. They were also asked to write open-ended comments on aspects of the interface that were helpful and aspects that were problems.

At the end of the experiment, after experiencing each interface, participants were given the same ten interface characteristics and asked to order the interfaces by how well each interface expressed each characteristic. They were again given a final opportunity to write open-ended comments on what was helpful or problematic for each interface and how the interface might be improved.

5.3.3 Procedure

Each of the twenty-four participants was given a consent form to read and sign. A questionnaire was given to each user to collect basic demographic information and assess their experience with computers, 3D graphics, speech recognition, and gesture interfaces. Participants were then shown a set of thirty symbols and asked to assign each a simple one word name. This allowed participants to become familiar with the set of symbols they would see during the task.

Participants were given several minutes to become familiar with each interface before starting the task. For interfaces involving speech recognition, they read the command list to ensure that they were familiar with all commands and the speech recognition process was working properly. They were allowed to try all commands and also practice navigation by finding and zooming in on Lake Okeechobee in Florida.

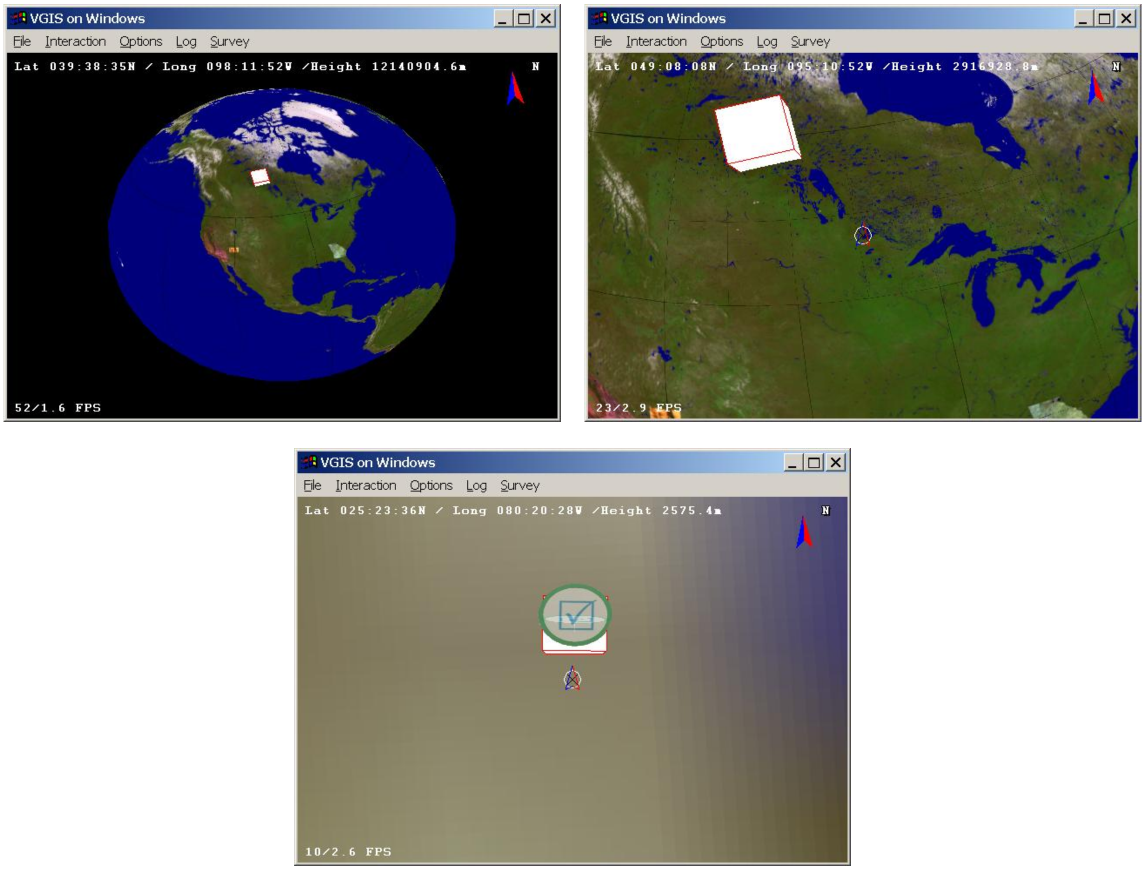


Figure 12: A sequence of images from the experimental task used in the multimodal interface study

Participants were informed of the nature of the interface task and told to pay attention to symbols, location, and order of presentation. Participants began in a stationary position about twelve thousand kilometers above North America (see Figure 12). When an interface task began, a white cube appeared at a location in North America. As participants navigated closer and zoomed in, the white cube began to shrink. Eventually, the cube revealed a disc with a symbol. When the participant came to within about 4 kilometers, a chime sounded, signaling that the user had come close enough and should zoom out to find the next target. After four targets, a different chime sounded, signifying the end of the task. Participants were then given the memory recall test and after that, the post-task questionnaire. After all four tasks, the final post-experiment questionnaire was given.

5.3.4 Results

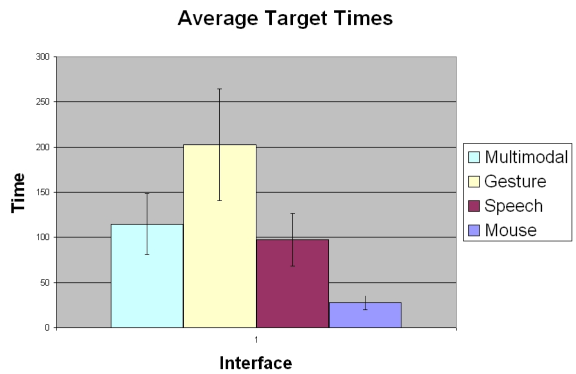


Figure 13: Average target time in seconds for each interface in the multimodal interface study.

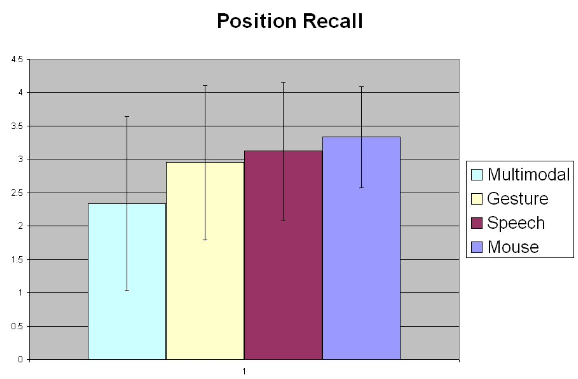


Figure 14: Average number of correctly recalled positions for each interface in the multimodal interface study.

A oneway ANOVA and a Tukey post hoc analysis of the objective results showed significant differences in average target time ($p = 0.001$). The average target times of all of the interfaces were significantly different with the exception of the speech interface and multimodal interface. The mouse interface was significantly faster than the others. All these results are illustrated in Figure 13.

The same type of statistical analysis also showed a significant difference in recall of the target locations ($p = 0.013$). The mouse interface and multimodal interface were significantly different. However, the other interfaces were not significant different. Furthermore, no significant differences among the interfaces were found at the ($p < 0.05$) level for symbol recall or order recall.

Participants were also questioned about ten interface characteristics on post-task and post-experiment questionnaires. The results were consistent although the post-task questions were on a five point disagree-agree scale and the post-experiment questions asked respondents to rank the interfaces. The mapping of the responses were as follows (-2 Strongly Disagree, -1 Disagree, 0 Indifferent, 1 Agree, 2 Strongly Agree). An ANOVA and a Tukey post hoc analysis was performed to determine if the mean responses significantly differed between interfaces.

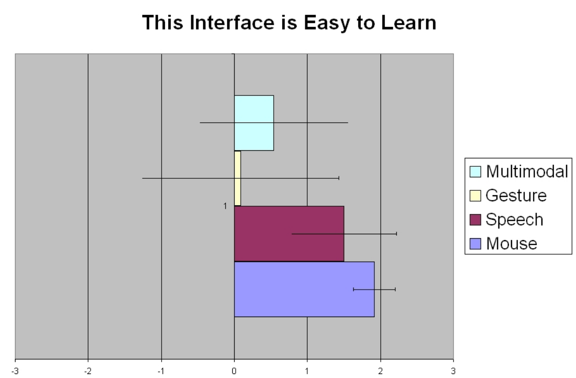


Figure 15: Questionnaire response to ease of learning for each interface in the multimodal interface study.

5.3.4.1 *Ease of Learning*

For the ease of learning characteristic (Figure 15), the interfaces fell into two groups. The participants felt that multimodal and gesture interfaces were not as easy to learn as speech and mouse. No significant differences were found between multimodal and gesture nor were there differences between speech and mouse.

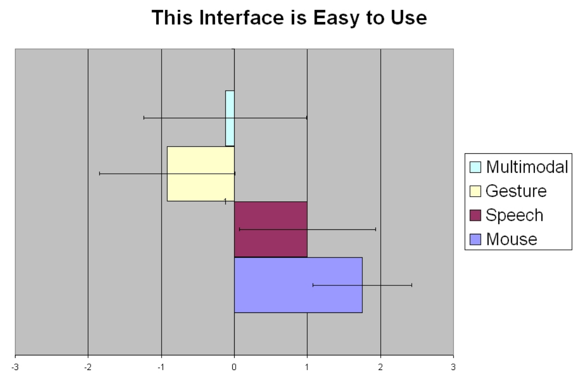


Figure 16: Questionnaire response to ease of use of each interface in the multimodal interface study.

5.3.4.2 Ease of Use

Participants' responses for the ease of use question were significantly different for each interface. The ranking of the interfaces from easiest to hardest was mouse, speech, multimodal, and gesture (Figure 16).

5.3.4.3 Errors

The speech and mouse interfaces were not significantly different in the participants' responses about error (Figure 17). However, the speech and mouse interfaces were better than the multimodal interface which was also better than the gesture interface.

5.3.4.4 Speed

The participants' responses concerning the speed of the interfaces (Figure 18) did reflect the objective measurements of average task time. The speech and multimodal interfaces were not statistically different. The mouse interface was felt to be fastest and the gesture interface was felt to be slowest.

5.3.4.5 Precision

The participants' evaluation of the precision of the interfaces paralleled their evaluation of the speed (Figure 19). Again, the speech and multimodal interfaces were not statistically different. The mouse

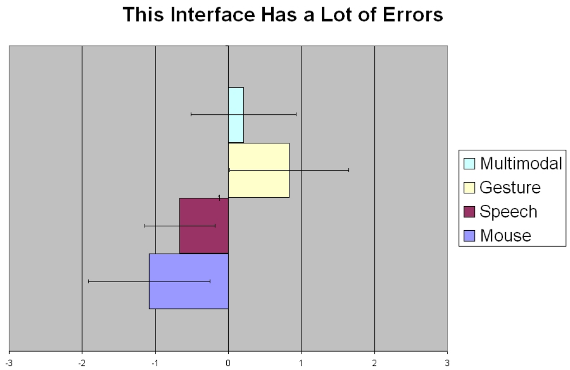


Figure 17: Questionnaire response to error rate of each interface in the multimodal interface study.

interface was felt to be most precise and the gesture interface imprecise.

5.3.4.6 Cognitive Load

The multimodal interface was considered to provide the most interference of remembering the symbols (Figure 20). The mouse was evaluated as providing the least. This was also reflected in the location recall analysis. The gesture and speech interfaces did not significantly differ.

5.3.4.7 Effectiveness

Users strongly felt that the mouse interface was effective. Their responses for each of the interfaces were significantly different (Figure 21). The second highest support was for the speech interface followed by the multimodal interface and the gesture interface.

5.3.4.8 Presence

The participants were asked whether "This interface gives me the sensation of being in the map, i.e. I am present and part of the virtual environment." This was an attempt to determine if any of the interfaces improved the sense of presence in the visualization. However, there were no significant differences in opinion between the interfaces (Figure 22). The environment did not seem to become more immersive with any of the interfaces. It is also possible that the question was confusing to the respondents.

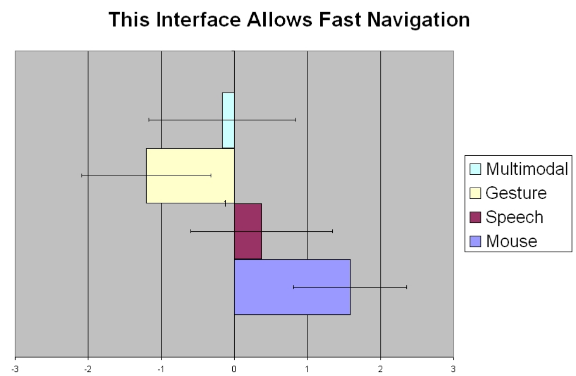


Figure 18: Questionnaire response to speed of each interface in the multimodal interface study.

5.3.4.9 Comfort

The most comfortable interface appears to be the mouse interface followed by the speech interface. The multimodal and gesture interfaces appear to be the least comfortable to use. User responses distinguished all but the multimodal and gesture interfaces; they appear to be equally uncomfortable under statistical analysis(Figure 23).

5.3.4.10 Desirability

After using and considering the characteristics of an interface, the participants were asked if they would like that interface on their own computers. The mouse was rated significantly higher than the other interfaces. The speech interface was second, but still significantly higher than the gesture and multimodal interfaces. The difference between attitudes towards the gesture and multimodal interfaces were not significantly different (Figure 24).

5.3.5 Conclusions

The familiarity of the mouse interface was one reason why the participants favored that interface. A few users were able to complete the navigation with the mouse so fast, they commented that it was difficult for them to recall targets. However, this concern was not widespread and was not reflected in the objective recall measures.

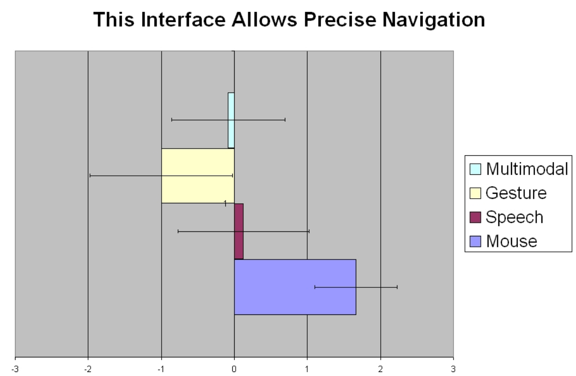


Figure 19: Questionnaire response to precision of each interface in the multimodal interface study.

Overall, the speech interface was well regarded. The recognition lag in the speech interface was a source of difficulty for participants. Participants occasionally had to repeat commands and give some commands early to anticipate for lag. Precision was somewhat difficult, but users could adjust.

The gesture interface seemed to be the most difficult interface for the users. Errors in the recognition were a large source of problems. Precise movement was very difficult. Furthermore, some participants found it even uncomfortable to point a forefinger upward and move it left and right. Some wanted to use a thumb or point the forefinger down.

The lack of integrated feedback for may have been a factor in the performance of the gesture recognition. Users were able to see the video captured by the Gesture Pendant. This may have helped the users understand the Gesture Pendant's field of view and also provide some feedback about gesture speed. If a user's hand quickly flashed on and then off the video screen, it would indicate that the user was moving too quickly. However, since the users in this experiment were attending to a navigation task, users might not be able to pay much attention to the gesture video. Placing the feedback were it can be noticed, perhaps onto the navigation display or into tactile or auditory sensory modes, might improve performance.

Since performing the task with gesture interface took far more time than any of the other interfaces, and since participants were only expected to spend about an hour on the experiment, several

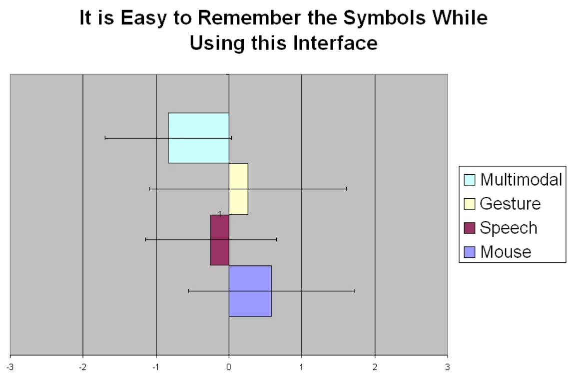


Figure 20: Questionnaire response to cognitive load of each interface in the multimodal interface study.

participants did not complete the task for the gesture interface. However, this did not seem to greatly affect the results of this study.

While the gesture recognition employed in this system was not very effective, other camera configurations and further developments of software and hardware may produce gesture recognition systems that are far more effective. Since the Gesture Pendant was designed as a prototype to explore on-body sensing, further exploration of navigation, using video based gesture recognition, is warranted.

The mouse and speech interfaces seem to rank highest by most measures. Of course, these interfaces are based on the most mature technologies. A few observations about the relatively low performance of the multimodal interface should be made.

While it is not surprising that the gesture interface was slowest and the mouse interface was the fastest, it is interesting to note that the speech and multimodal interfaces were not significantly different in speed. It was hoped that the additional expressiveness of the multimodal interface would have some benefit in speed. From the subjective results, it is apparent that the participants did not feel that the multimodal interface was more precise or faster than the speech interface. The addition of the gesture component did not improve performance. Furthermore, it hurt performance in some aspects. The multimodal interface was ranked most like the gesture interface in some subjective

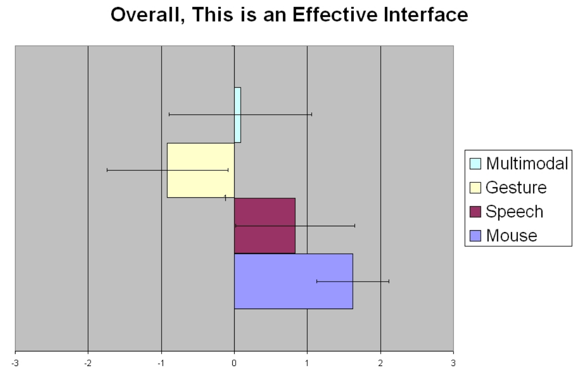


Figure 21: Questionnaire response to effectiveness of each interface in the multimodal interface study.

measures and indistinguishable from the gesture interface in ease of use, comfort, and desirability. The performance of the gesture component was certainly limited by the resolution of the video camera and the performance of the finger tip segmentation. A more robust and faster segmentation algorithm could significantly affect these results. More sophisticated hardware and software should be investigated since they would likely improve the performance of both the gesture and multimodal interfaces.

For the objective of use in a wearable computer application, where a mouse may not be available or handy, the results indicate that speech can be somewhat effective, at least for the extended navigation task presented. The results indicate that better gesture recognition is an important factor here and further work is needed to improve recognition. Different gestures should also be tried for improved comfort, ease of use, and precision. Furthermore, there may be other different or more complicated tasks where the increased expressiveness of a multimodal interface would pay off.

5.3.6 Future Work

Future work would be to address the problems and limitations of the gesture interface. Both hardware and software enhancements are possible. Recognition might improve if the Gesture Pendant could capture and process 3D data. This could be accomplished through a stereo camera pair. Depth information could be used to better segment the nearby hand silhouette from more distant infrared

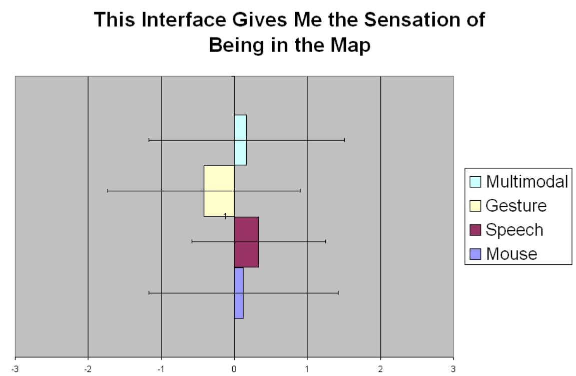


Figure 22: Questionnaire response to presence of each interface in the multimodal interface study.

light sources and reflections off highly reflective objects. Depth information would also allow gestures along the Z axis and allow better differentiation of the wrist and finger tips. An alternative approach would be to use a single camera and a visible laser projected into a grid pattern. Measuring deformations in this structured light would allow 3D imaging of the hand. This would have the additional benefit of visibly illuminating the camera's field of view so users would know when their hand was visible to the camera. Also, this configuration could allow outdoor gesture use. While sunlight's broad spectrum and intensity overwhelms the current Gesture Pendant's infrared illumination, the visible laser may be intense and narrow band enough for outdoor use.

5.4 Two Handed Interaction

Another set of candidates interfaces may employ two handed interaction. At first glance, this seems antithetical to the goal of leaving a wearable computer user's hands unencumbered. While it is best to leave the hands of a wearable computer user unencumbered, interaction devices that can quickly be engaged and disengaged may be satisfactory. Devices such as the isometric joysticks in this study, are small and can be mounted on rings for the fingers. This study also examined a one handed interface, for situations where encumbering two hands is not acceptable.

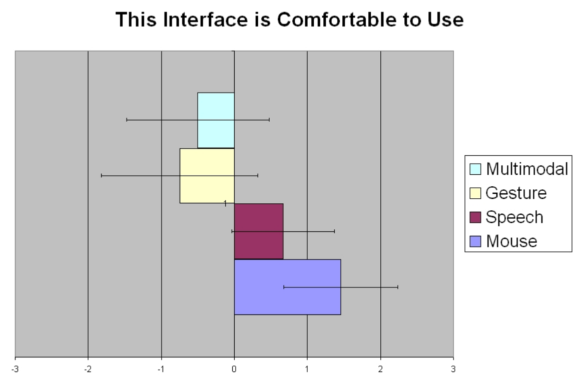


Figure 23: Questionnaire response to comfort of each interface in the multimodal interface study.

5.4.1 Related Work

There is a long history of using 2D devices to interact in 3D environments which came about because 3D devices were not widely available. Early 3D object manipulation techniques for 2D controllers include Chen's Virtual Sphere [24], Shoemake's Arcball [130, 129], and Houde's techniques for 3D object manipulation [58]. Mackinlay's Point of Interest navigation technique [84] used 2D input devices as did Zelesnik and Forsberg's UbiCam camera control system [168]. The interaction techniques in the present study were based on particular techniques from Zeleznik's earlier discussion [169] of 2D devices for 3D object manipulation and navigation, and Zhai's "bulldozer" navigation metaphor [170] that used two 2D joysticks. These techniques were selected because they are more appropriate for a wearable computer display. They do not require direct reference to points on the display, which is difficult with eyeglass-mounted wearable displays. Nor do they use cursors, which can be easily lost on an eyeglass-mounted display.

We have also employed a tilt sensor for two of our 3D navigation methods. Tilt sensors often function as part of position and orientation tracking systems for virtual and augmented reality. However, tilt sensors have also been used to augment a variety of input devices as they were being employed in the present study. Balakrishnan developed a curved bottom "Rockin' Mouse" [8] which allowed additional tilt input. Masui and Siio [90] created a Fieldmouse, implemented as a

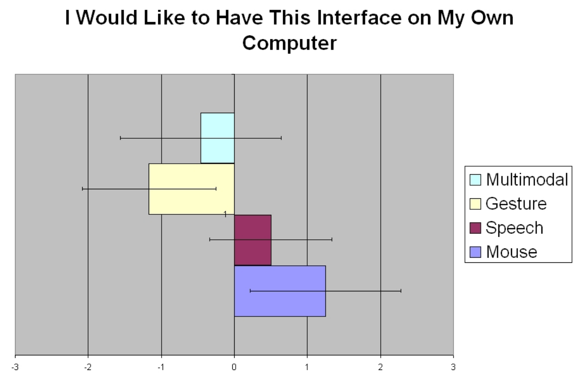


Figure 24: Questionnaire response to desirability of each interface in the multimodal interface study.

tilt sensor and barcode reader, as part of a "Real-world GUI" to control household and informations appliances. A number of researchers have worked with PDA's and other small screen interfaces with tilt sensors. Rekimoto [115] used a tiltable display for 2D GUI operations, 2D navigation, and 3D object inspection. Bartlett [11] explored scrolling and other GUI operations. Hinckley et al. [53] used a variety of sensors (tilt, IR proximity, and touch) to augment a handheld computer for adjusting screen configuration, launching applications, and scrolling the display. However, tiltable display interfaces are not amenable to eyeglass-mounted wearable displays.

Ted Selker and others developed the IBM trackpoint, a popular isometric joystick [122]. Kawachiya and Ishikawa [65] explored isometric joystick input for mobile information browsing using the ScrollPoint, based on the IBM TrackPoint. However, they focused on 2D operations like pointing and scrolling for a small handheld display. The focus of the present study was 3D navigation for a 3D wearable computer application.

5.4.2 Method

5.4.2.1 Participants

Twenty-seven students from an introductory computer graphics course participated in the user study. The data for three students were disregarded due to equipment difficulties or prior experience with a similar study. Of the twenty-four final participants, there were twenty-two males and two females.

There were some PhD and MS students, but the majority were junior or senior undergraduates. Accordingly, the age range was 18 to 27, with a mean of 22.

All participants were frequent computer users. The majority had some familiarity with 3D interfaces. Most were frequent players of first person shooter games, and a lesser number were frequent real-time strategy game players. However, most had seldom or never used 3D design software.

5.4.2.2 Apparatus

Figure 25: A typical eyeglass mounted wearable computer display.

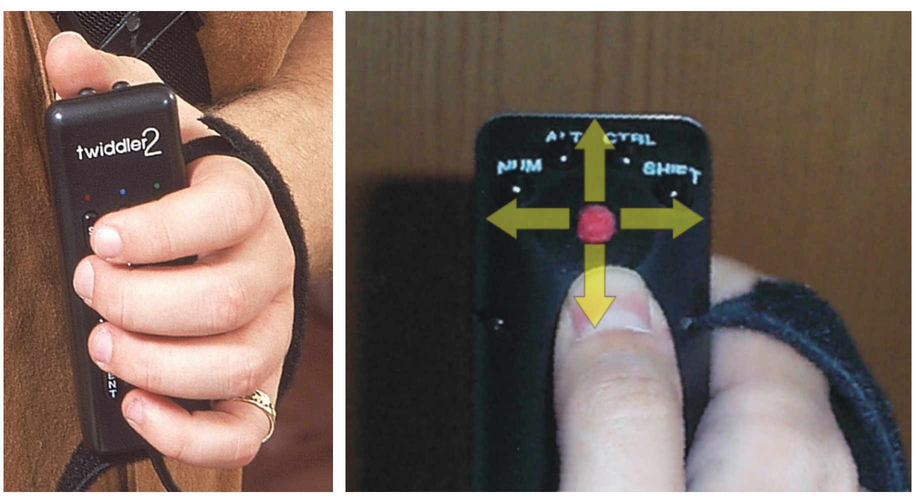


Figure 26: A chording keyboard with isometric joystick often used in wearable computers.

Four interfaces were developed using the isometric joystick on the HandyKey Corporation's Twiddler2 chording keyboard. The four interfaces allowed for navigation in both exocentric (downward looking viewpoint) and egocentric (first person viewpoint) modes. Since these modes have different characteristics, for example, pitch and yaw have less utility with a top-down viewpoint, a particular interface should have different mappings specific to the viewpoint.

These interfaces did not use any of the keys available on the Twiddler2. There were two reasons for this. First, it is easier to engage the keys or the pointer separately rather than in combination. Either the fingers can help hold the Twiddler2 while the thumb is using the isometric joystick, or the thumb can help hold the Twiddler2 while the fingers press the keys. Second, these interfaces were designed with an eye towards a possible future device design. This would be unobtrusive pointer devices on rings, as in IBM's TrackPoint on a ring prototype, that allow a user to quickly begin interaction with a computer application and then just as quickly go back to manipulating objects in the real world. Since the pointer is operated by a thumb, extra buttons could not be engaged simultaneously.

The first interface uses a "bulldozer" metaphor, as in Zhai [170], which requires simultaneous input from both hands to initiate movement. This reduces the chance of accidental input which is important in wearable computing. Furthermore, this interface allows a user to control many degrees of freedom (x, y, z, and yaw).

A second interface uses an airplane metaphor which reflects a common control paradigm in 3D environments, due to the prevalence of aircraft and also games involving flight simulation. In this interface, the right hand controls pitch and yaw. The left hand controls forward and backward movement.

Two other interfaces were developed that added a tilt sensor to the Twiddler2. Inexpensive accelerometers were chosen rather than more exotic orientation trackers or other trackers with full position and orientation data. These are quite expensive and would not be very convenient due to weight and bulk related to the necessary fixed transmitters.

The tilt sensor was used as a binary mode switch between panning and elevation. With the tilt sensor, the joystick's plane of motion represents the plane of navigation. For the current study, the use of the tilt sensor as a proportional panning or zooming control was avoided as this use might not be effective for wearable computer users who may wish to gesture as a part of conversation or use the input device in various positions (hand behind the back, in a pocket, sitting, walking, etc.) However, this type of control could be explored in future studies.

The third interface combined the bulldozer metaphor with tilt. In the basic bulldozer interface, the mapping for zoom is not very intuitive because the bulldozer metaphor becomes forced. A user zooms in by moving the left and right joysticks apart laterally. This was addressed in the bulldozer with tilt interface by using the tilt sensor to select between horizontal and vertical motion. For example, when the joystick is held horizontally, forward pressure causes forward motion. When the joystick is tilted vertically, forward pressure causes vertical motion.

The final interface combined the airplane style of interface with tilt. The tilt sensor was used to select between horizontal and vertical motion. In this interface, only a single isometric joystick and tilt sensor was necessary for controlling zoom, elevation, and yaw.

While a wearable computer and head mounted display form the target platform of these navigation techniques, a desktop PC and monitor are sufficient for evaluation. The equipment used in the user study consisted of a PC (2.4 GHz Pentium 4, Windows 2000) running VGIS, a whole Earth 3D terrain visualization system[82]. VGIS provides efficient level of detail management, allowing real-time interaction with large global datasets. Such datasets include terrain elevation, terrain phototextures, and 3D building models. A second Linux workstation captured input from the two isometric joysticks and the tilt sensor. This data was sent as UDP packets over a LAN to the VGIS system. There were four interface configurations as described previously: the two handed bulldozer interface, the two handed airplane interface, the one handed airplane interface with tilt sensor, and the two handed bulldozer interface with tilt sensor.

5.4.2.3 Experimental Design

Many criteria can be used to compare and measure these interfaces. Factors like speed, ease of learning, precision, and comfort are important, so travel times were recorded and questionnaires were employed. Another important criteria for interfaces is cognitive load. If the interface is difficult to use, it may require a large percentage of a user's cognitive resources. One widely used result of cognitive psychology shows that there are severe limitations on working memory capacity [92].

Furthermore, when individuals are forced to use working memory or other cognitive resources, information is lost or displaced [6]. It is therefore vital that the interface to a wearable application have low demands on cognitive load because the application is already secondary to a user's real world task and surroundings. A visual memory task was used to assess the cognitive load of the interfaces since cognitive load will be reflected in the quantity of information that can be remembered.

Each participant performed a two part navigation task with each of the four interfaces. The interfaces were presented to the participants in every possible order, to balance any order effects, such as learning or fatigue. Each participant performed each of the navigations with different target layouts. The 8 different target layouts were also presented random order for each participant.

5.4.3 Procedure

Participants were first given a questionnaire to ascertain their experience with 3D computer applications such as games and 3D design software. Next, participants were given a standard test for visual memory [35]. This was done to assess the visual memory abilities of each participant before performing the study's navigation task. After the memory test, they were shown a set of 30 symbols and asked to write down a simple name for each of the symbols. This was done to ensure that each subject had a similar level of familiarity with all of the symbols since the symbols would be a part of the visual memory test.

Participants were first introduced to a particular interface and shown how to navigate. They were also given an explanation of the navigation task and the testing that would occur afterwards. The first part of the navigation task was exocentric, so the viewpoint was locked into a downward looking direction. Participants began with an orbital view of North America. The task began when a white target cube appeared somewhere in North America (Figure 27). Participants were asked to zoom in on the target. As the participants drew closer, the target became smaller and smaller, until a symbol was revealed. A chime signaled when the user was close enough to the target. This movement typically involved a twelve thousand kilometer descent. Participants zoomed out, located the next target, and zoomed in again. Four targets were presented. Afterwards, they were given a test requiring them to recall the symbols they encountered, the order in which they were presented, and their locations.

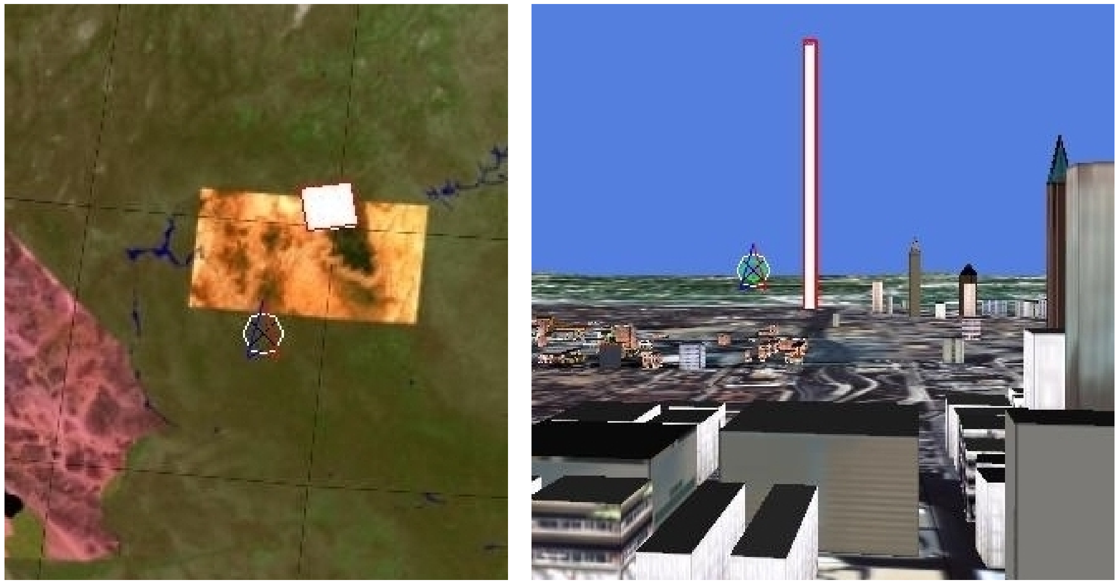


Figure 27: For the isometric joystick study, a cube was the exocentric task target. A column was the egocentric task target.

In the egocentric portion of the navigation task, users were placed south of the city of Atlanta, facing north. Since self-location is more difficult with an egocentric viewpoint, the participant was shown several landmarks in both the visualization environment and the paper map used for testing. These included two major highways, the Georgia Tech campus, downtown Atlanta, and a stadium. A similar four target task was used, but with tall white columns instead of cubes for visibility in the city skyline (Figure 27). Again, participants were given a test requiring the participant to recall the symbols encountered, the order, and the symbol locations.

Participants were then given a questionnaire to score the interface on a variety of characteristics such as speed, ease of use, ease of learning, comfort, precision, errors, and desirability. There were also two open response questions to allow the participants to comment on what they liked and disliked about the interface and how the interface might be improved.

After experiencing all four interfaces, the participants were asked to rank the interfaces on the same set of characteristics as before, and given a final opportunity to write any other comments.

5.4.4 Results

The time for a user to acquire and travel to each target was recorded. The mean target times for each interface in both exocentric and egocentric modes are shown in Figure 28. Under ANOVA, mean travel times in the exocentric mode showed significant differences for interface type ($p = .008$). However, no significant differences were found for interface type in the egocentric mode. A Tukey post-hoc comparison showed that the exocentric airplane interface target time was significantly smaller than the exocentric bulldozer and exocentric airplane with tilt interfaces. The bulldozer with tilt interface was not significantly different from the other exocentric interfaces.

While it is tempting to compare the exocentric interfaces as a group with the egocentric interfaces and conclude that the egocentric interfaces were faster, such a comparison can not be made. The two groups of interfaces were used in two different tasks. The egocentric interfaces were used to navigate around a virtual model of Atlanta. The exocentric interfaces were used to navigate across the entire North American continent. Task differences make it to directly compare user performance between the two interface groups. Different tasks were used because certain tasks call for particular navigation perspectives (exocentric or egocentric). For example, it would be very difficult to navigate across a continent with an egocentric perspective. However, a user may wish to use an egocentric perspective while navigating and familiarizing herself with the smaller region of a city.

Users were asked to recall target symbols, locations, and order. Mean scores for each interface are shown in Figure 29. There were no significant differences between interfaces at the $p < .05$ level within the egocentric or exocentric tasks.

We did not find scores on the visual memory test to be predictive of target recall. There did not appear to be linear relationships between test scores and recall scores. Correlation was also low, ($0.0005 \leq R^2 \leq 0.3263$), for any particular interface and navigation mode (egocentric or exocentric).

Participants rated each interface on several characteristics immediately after use. At the end of the experiment, users assigned relative rankings for all interfaces on these same characteristics. Ratings and rankings for the interfaces were consistent, with only minor shifts of interface order. Selected final rankings are shown in Figures 30 to 33.

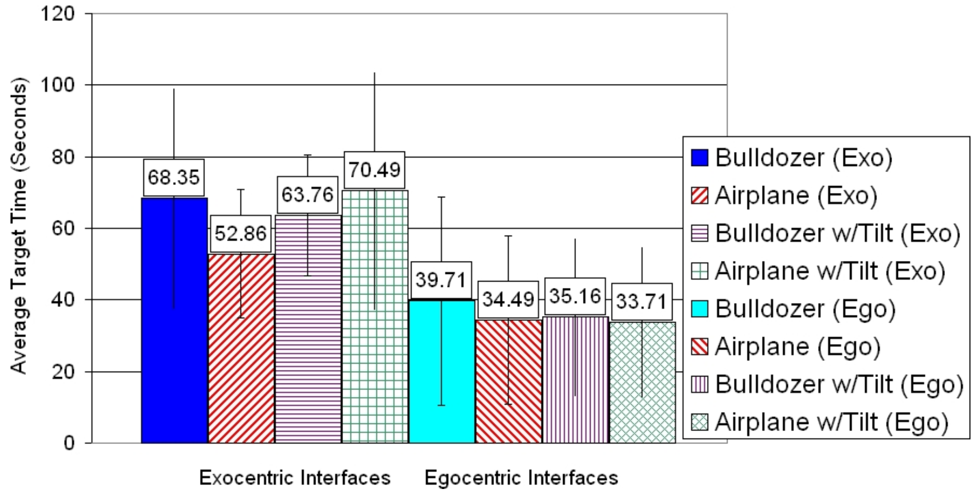


Figure 28: Average travel time to each target for each isometric joystick interface.

Participants made a number of informative suggestions and comments about the input device and interface characteristics. Since user participation flagged at the end of the study, discussion will focus on comments written by participants immediately after using each interface. The participants made approximately the same number of total comments about each interface (39 to 44).

The bulldozer interface received 22 negative comments out of 39 total comments (56.4%). The most common negative comments included pain or difficulty in using the isometric joystick (6, 15.4%), and difficulty in zooming in and out (5, 12.8%). The most common positive comments included the ability to pan and zoom simultaneously (7, 17.9%), and ease of learning (4, 10.3%).

Participants gave the airplane interface 19 negative comments out of 43 (44.2%). Eight negative comments (18.6%) focused on joystick pain and difficulty. Nine positive comments (20.9%) cited the ability to pan and zoom simultaneously. Eight other comments (18.6%) positively highlighted the use of two separate controllers for zoom and panning.

The bulldozer with tilt interface received 42 total comments, 27 (64.3%) were of a negative nature. The negative comments focused the inability to zoom and pan simultaneously (6, 14.3%) and difficulty in learning and using the tilt sensor (6, 14.3%). Seven positive comments (16.7%) mentioned the separate modes for zoom and panning.

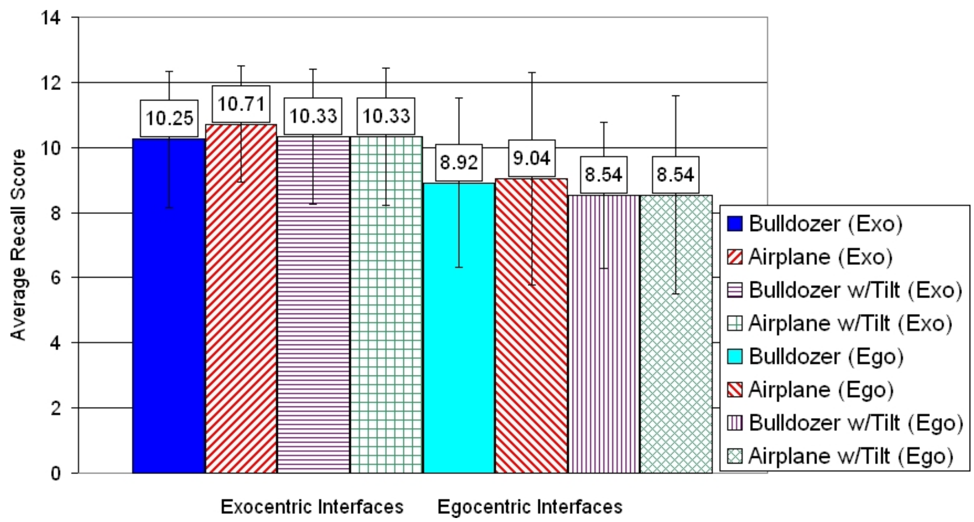


Figure 29: Average recall score for each isometric joystick interface.

Participants wrote 29 negative (65.9%) of 44 total comments about the airplane with tilt interface. There were three negative topics that each garnered eight (18.2%) comments each. There were problems encountered with learning and using the tilt sensor, pain and difficulty using the joysticks, and the inability to simultaneously pan and zoom. Positive comments included the ability to use one hand (4 comments, 9.1%) and the separate modes for panning and zooming (4 comments, 9.1%).

Many participants cited pain and difficulty in using the isometric joysticks. This is of great concern. Isometric joysticks sense force, instead of displacement. More speed requires more force. They may be appropriate for occasional laptop cursor navigation, but may not be a good match for tasks with sustained input. This may have caused a problem for the study participants.

There is a seeming contradiction in the responses to the tilt interfaces. Users liked having the ability to simultaneously pan and zoom and they also liked having different modes that separated panning and zooming. This probably means that users wanted simultaneous pan and zoom while having precise and independent control of each degree of freedom.

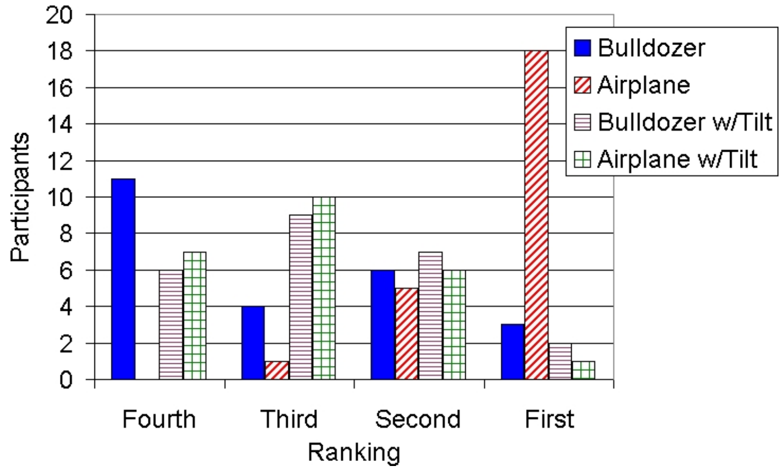


Figure 30: Questionnaire response to ease of use of each interface in the isometric trackpoint study.

5.4.5 Conclusions

The original hypothesis was that the airplane-like interfaces would encourage better performance in speed and information gathering. It was also felt that adding the tilt sensor would also be advantageous, particularly for the bulldozer interface, since that would present a simpler conceptual model. The hypothesis was that pressing the joysticks when the controllers are tilted is a simpler mapping to altitude control than lateral force. This simpler mapping would then have measurable effects on performance. However, we only saw statistically significant results for exocentric target times, but not for egocentric target times, nor for memory recall. Closer examination of both the objective and subjective results yields a better understanding and some interesting conclusions.

Target times are shown in Figure 28. In the exocentric task, the ability to pan and zoom simultaneously was probably the most important factor because the interfaces with the tilt sensors had significantly longer exocentric target times than the airplane interface. While not significantly different, the bulldozer interface's exocentric target time was worse than the airplane interface but better than the interfaces with tilt sensors. The bulldozer interface allowed some simultaneous pan and zoom, it was more difficult to perform since users had to press the joysticks apart laterally and

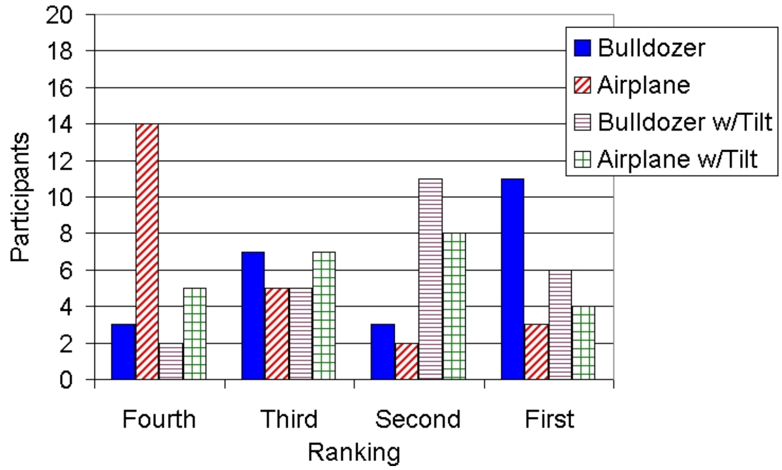


Figure 31: Questionnaire response to error rate of each interface in the isometric trackpoint study.

then adjust the ratio of and direction force between each joystick for panning. For exocentric navigation, zooming and panning are both equally important, and this must be reflected in the interface design.

There are several potential explanations for the lack of significant differences in egocentric target times. Since targets were located in the same city, users did not have to travel far or for very long, reducing sensitivity to interface effects. Another factor is the difficulty in maintaining awareness of location. This was less of an issue in the exocentric task since users could identify a target location at some time before or after reaching a target, based on the familiar features of the North American continent. The Atlanta cityscape is more complex due to the higher number of features such as buildings and roads, as well as the 3D nature of the skyline. Some participants navigated the environment, both before and after reaching a target, in order to acquire or maintain self location and bearing. This variance may have overwhelmed lesser effects of the interfaces on travel time.

There may have been some benefit, however for the tilt interface in the egocentric task. Since the egocentric task could be performed with minimal adjustment to altitude, isolation of the altitude control may have been a beneficial feature. While there were no significant differences in means, the bulldozer interface had the highest egocentric travel time. It is possible to inadvertently change

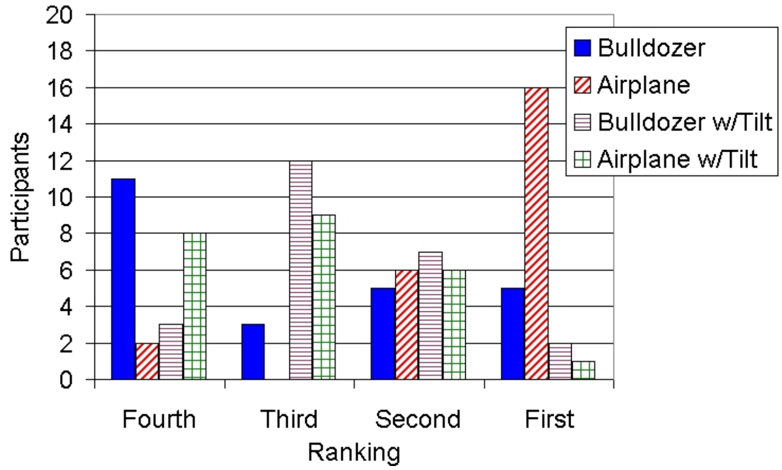


Figure 32: Questionnaire response to precision of each interface in the isometric trackpoint study.

altitude in the bulldozer interface while specifying forward or backward motion. More time would be spent re-adjusting altitude. The tilt interfaces would not be subject to this. Further investigation would be necessary to explore this factor and separate it from the effect of acquiring and maintaining self location and bearing.

The lack of significant differences for target recall may be due to two causes. There appears to wide variation in spatial abilities in the general population. Also, while the task required participants to remember the symbol, order, and location for four different targets, this measure may not have been sensitive enough to reflect interface type effects.

5.4.5.1 Design Guidelines

These experiences have produced a few guidelines to help develop and select methods of interaction for 3D environments on wearable computers.

Separability: Users like to have separability or orthogonality of control for different axes. The participants in the study did not like the bulldozer interface. If users pushed forward with both joysticks, some change in altitude would also occur since users would also be pushing the joysticks slightly apart or slightly together. This was one reason why participants favored the airplane interface: they could easily make adjustments to one particular axis at a time.

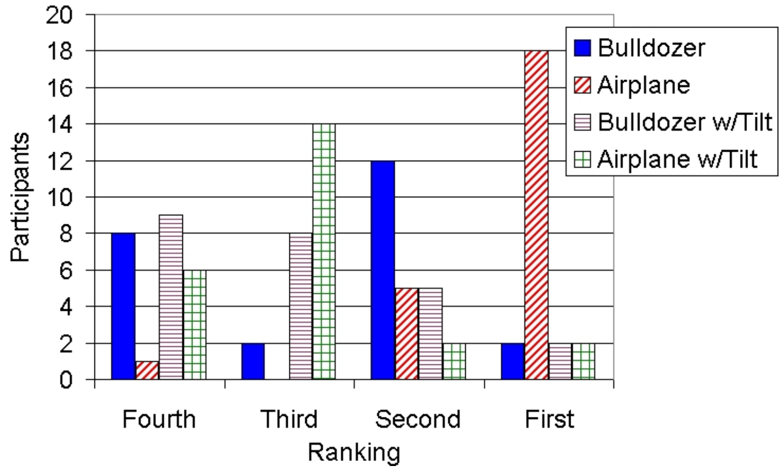


Figure 33: Questionnaire response to comfort of each interface in the isometric trackpoint study.

Composition: However, an interface with separability should also allow composition. Users also like to be able to compose commands together in parallel rather than sequentially. This allows faster adjustments to position and makes interface less modal. In the airplane with tilt interface, users could zoom in, or pan, but not both at the same time. Since we were using only one 2DOF isometric joystick, this was a limitation of the hardware, but users still asked for the ability to control 3DOF simultaneously.

Symmetry: In the bulldozer interface, it was often necessary to apply the same force and direction to each joystick to move in a given direction. Users found it difficult to fulfill this symmetry requirement. There are usually differences in dexterity and strength between the dominant and non-dominant hand. Furthermore, there can be differences in the mechanical properties of particular isometric joysticks. This would not normally be noticed since a user would adjust to the single particular joystick being used. However, it was an issue in our study. A standard joystick, which is not isometric, might not be as sensitive to such differences. A calibration process might address this issue.

Display Reference: Some interfaces require the user to make reference to a particular location on a screen. This can be done directly by pointing a finger, wand, or stylus at the screen. This is a useful and simple technique, but some occlusion of the screen may result. Furthermore, precision becomes an issue for screens that subtend a small visual angle. For head mounted displays, as in our target system, the user can not touch the display surface easily. Any form of direct reference is difficult since it requires accurate tracking of the hand or pointing device. An alternative is to do this reference indirectly, with a cursor. However, users found it fatiguing and difficult to precisely position the cursor over small GUI elements. The cursor may be small, fast moving and thus difficult to see and control in head mounted displays. It may be necessary, as in this study, to set a crosshair at the center of the display. All movements are in relation to this center point, thus, avoiding cursor and direct reference issues.

Handedness: Humans often use both hands in combination. It can be useful to employ this ability in two handed computer interfaces. Consideration must be made as to whether each hand has similar or dissimilar tasks. Since most individuals have a dominant and non-dominant hand, a careful mapping of dissimilar tasks can be useful. The bulldozer interface explored similar tasks; however, some users commented that the non-dominant hand seemed superfluous. The airplane interface mapped dissimilar tasks to each hand. One method of mapping these tasks is suggested by Guiard, who noted that in handwriting, the non-dominant hand provide a frame of reference for the dominant hand's activity [49].

However, two handed interfaces make it more difficult for wearable computer user to grasp or interact with objects in the real world. The disadvantages of the airplane with tilt interface might be acceptable since it only requires a single hand. Many wearable computer users will often hold the Twiddler2 keyboard in their non-dominant hand so the dominant hand can remain free. It is often important for users to be able to quickly engage and disengage their hands from the interface. This allows users to engage in social interactions, such as handshakes, and perform real world tasks such as construction, inspection, and maintenance, which require the manipulation and examination of objects.

Manner of Operation: With a desktop interface, the interface designer can expect or prescribe a relatively static pose for the user. However, wearable computer users may be walking, standing, or sitting. They may hold their hands in a variety of locations. Sometimes they will hide their hands so that operating the interface is not socially disrupting. One of the design issues with the tilt sensor was defining upright and tilted positions. This differed between users and between standing and sitting postures. With a direct mapping of tilt to altitude, user fatigue would increase since users would have to concentrate on keeping their hand steady, and accidental movement would be more common. These problems were not encountered in tiltable displays because the user is prone to maintaining a relatively constant angle in order to see the screen. Some users may just not have very steady hands, particularly when they are operating a small thumb joystick or chording keyboard. There may be coincidental and sympathetic motions of the hand.

Comfort: Comfort is a prime consideration, especially since users will have wearables with them for several hours a day. Size of the controller is a concern since a slight fit problem may cause great discomfort over time. Several users in our study found it awkward to place the thumb on the joystick control in an appropriate position for operation. Duration and frequency of device use will have a contribution to discomfort and fatigue, which may not be apparent until a realistic task scenario is performed, or the graphical environment scales up in size and complexity. With small 2D or 3D environments, users need not navigate for very long periods. However, some extended 3D environments, as in this study, cover a large distance and magnitude of scale (a whole Earth model from planetary to millimeter scale). The frequency and duration of device operation is probably quite high in such an environment. This may be why fatigue and discomfort is more of an issue with the isometric joystick in this system than in standard 2D GUI operation.

Input Sensors: Input sensors should be carefully selected so that their properties match well to the user and the nature of the task. Two types of sensors were used in this study, isometric joysticks and a tilt sensor, implemented with an accelerometer. Several characteristics of these sensors have a great deal of impact for navigation tasks.

The isometric characteristic of devices like spaceballs and isometric joysticks may lead to comfort and fatigue issues. Since these devices sense force, rather than motion or displacement, users may apply a great deal of force to navigate quickly. Feedback is not in the form of displacement, but in the form of resisting pressure which can be fatiguing. In one handed operation, some users used the second hand to steady or even operate the joystick. Many also reported sore thumbs. The dynamic range of the input sensor may not be large enough to allow both fine control of speed as well as the desired range of speed. These factors may suggest that isometric joysticks are better suited to small environments such as 2D GUI's and low frequency, short duration tasks. As reported above, the bulldozer interface had difficulties due to calibration. Many users suggested using miniature joysticks more like those on video game controllers. Devices like these joysticks sense displacement rather than force, and might be less sensitive to calibration differences. They may also be less fatiguing, provide better feedback, and have a potentially larger dynamic range. However, such joysticks, as well as trackballs, might inadvertently move as the user walks or lightly brushes the controls. Such noise can disrupt position and orientation control.

While accelerometers can be small and do not require direct operation by a finger or thumb, they do have some drawbacks. Feedback relies on the user's proprioceptive sense of tilt. This may work well for gross angles, but small angles may be difficult for proprioception. Some tilt sensors may have some pendulum characteristics, adding noise and making direct control of position or orientation more difficult. Furthermore, a user in a mobile environment may experience many forms of acceleration (walking, riding in a car, etc.) which can affect the sensor. Some accelerometers have integration functions to reduce noise, but this may dampen fine adjustments that the user may be making. These characteristics make it difficult for precise control with tilt sensors.

5.5 Summary

This chapter examined ways for users to navigate inside a wearable computer based terrain visualization. Such a visualization is an important component of a spatial cognition aid. Navigation within the visualization is quite important to users who must explore the surroundings and peruse areas before visitation. These experiments suggested the use of speech as an effective interaction mode as well as a two handed interface with aircraft-like control mappings.

Such interaction techniques can service the user to wearable computer relationship component of a wearable computer based spatial cognition aid. The following chapter will examine another relationship from the relationship mediation model that is key for spatial cognition aids. The next chapter discusses how a wearable computer can mediate the users relationship with the environment and improve a user's spatial cognition.

CHAPTER VI

INFORMATION PRESENTATION FOR SPATIAL COGNITION

6.1 Introduction

This dissertation has raised the notion of using wearable computers as a platform for a spatial cognition aid. Previous chapters have also discussed building blocks for this application: how wearable computers can gather information about the environment from a scalable system of data servers, and how users of wearable computer based visualizations can navigate through their visualizations.

With the previously described components, a wearable computer can provide an interactive visualization that is populated with weather, traffic, buildings, the location of other users, and an endless variety of other environmental information. However, these capabilities are meaningless if humans can not understand that visualization and use that information to perform more effectively. An effective information presentation must be developed and validated.

This chapter will discuss how wearable computers should present environmental information to the user. In the relationship mediator model from Chapter III, this is the wearable computer acting in the role of mediator between the user and the environment. This chapter will present the major design issues related to wearable computer based spatial cognition aids. This chapter will also examine related work for possible design guidelines. Finally, it will discuss studies that were performed to further develop and verify these design guidelines.

6.2 Design Issues

The most common spatial cognition aid is an ink and paper map. Maps are nearly ubiquitous among all human societies and have successfully guided generations of travelers. However, these maps are static. They can not show a user's changing position or changing orientation. With a wearable computer based spatial cognition aid, an interactive map can be displayed on the user's eyeglass mounted display. This map can take the form of a three dimensional virtual model of the user's surrounding environment. However, some important design issues emerge. For example, what viewpoint should be used in rendering this model? How should user orientation be reflected? For guidance, some related studies concerning ink and paper maps, electronic maps, virtual reality, and wearable computing will be considered.

A "You are here map" is a common aid. These maps are provided in such places as shopping malls, company and school campuses, and large office buildings. Levine's extensive studies of "You are here maps" [79, 80] suggest the following design rules for effective YAH maps:

- The two-point theorem states that a map reader must be able to relate two points on the map to their corresponding two points in the environment.

- The alignment principle states that the map should be aligned with the terrain. A line between any two points in space should be parallel to the line between those two points on the map.

- The forward-up principle states that the upward direction on a map (assuming it is mounted perpendicular to the floor) must always show what is in front of the viewer.

These guidelines can be applied to a wearable computer based spatial cognition aid. Since the wearable computer provides a virtual model of the surrounding environment, it should be possible for users to relate points in the model to points in the environment, satisfying the two-point theorem. A magnetic compass or other orientation sensor can be used to rotate the virtual model, satisfying the alignment principle. However, application of the forward-principle can be somewhat ambiguous because the virtual model can be rendered in different ways. It can be rendered from a top-down viewpoint, much like a traditional map, and displayed on the perpendicularly mounted wearable computer display. The forward-up principle would then apply. If a perspective viewpoint was used, the forward direction in the virtual model would correspond to the forward direction in the environment. No forward-up mapping would be necessary.

Further confirmation of the forward-up principle comes from a study of electronics maps and aircraft navigation. Aretz and Wickens studied the mental transformations required in a navigational checking task [3]. Navigational checking is the process of determining if one's position in the world corresponds to a particular location on a map. Since navigation systems are subject to some level of imprecision and failure, it can be important for a pilot to determine if a reported position is correct. The two experiments in the study were designed to determine the amount of mental processing required to determine if a particular electronic map was congruent with another scene. These experiments presented simplified scenes with both top down and perspective viewpoints. A map was presented with some rotation angle, either before, after, or simultaneously with presentation of the scene. The time required for the subject to respond with a congruent or non-congruent determination was measured. While the experiments did not confirm the proportional relationship between rotation angle and response time generally seen in previous mental rotation research [36, 40, 54, 79, 120, 128, 131, 162], they did show a monotonic relationship. Humans had the fastest performance if map and the scene were visible at the same time, and the map is given a forward up alignment, rather than a north up or other alignment.

However, some work in electronic maps suggest that the alignment principle may not always apply. A study of automobile navigation systems by Mashimo et al. [89], divided university students into two groups, a Fixing Group and a Rotating Group, based on how they drew a map of their school. It was felt that the rotating or not rotating the map was suggestive of the students' spatial orientation preferences, and thus how the students perceived and recalled their environment. In the driving portion of the study, participants were asked drive a route while following a map presented on an automobile navigation system. The system could display either a north-up map or a heading-up map. While only 4 students from each group participated in the driving portion, an interesting result is that participants in Fixing Group pointed out positive aspects about the north-up presentation. Members of the Rotating Group pointed out negative aspects of the north-up presentation. Mashimo et al. concluded that the display presentation should be adapted to the driver's spatial orientation. The results of this study might bear some consideration, however the study group size was rather small and the statistical analysis was not seem rigorous.

Other work in automobile navigation has examined the design question of top-down or perspective viewpoint. Spoerri evaluated a prototype automobile navigation display for communicating a sequence of turns to the driver [135]. These turns were presented as a series of arrows rendered with a perspective view, or a series of arrows in conjunction with a forward-up map of the city grid. Turn sequences in each of the displays were presented to study participants who were asked to remember and later reproduce the sequences. He found that directions presented with a perspective viewpoint, and in a user centered coordinate system, were easier to recall than directions presented in a global coordinate system and in conjunction with the map. User centered directions are in reference to the user's frame of reference, i.e. left, right. Directions in a global coordinate system are in reference to the environment, i.e. north, south, east, west. Spoerri concluded that such perspective displays would allow drivers to more easily integrate the directions with what they are seeing through the windshield. This suggests that a perspective display might be appropriate.

Some caveats must be observed in interpreting the results of Spoerri's study. While the ease of interpretation and memorability of such a display was demonstrated, other conclusions may not be so clear. The memory task in this study was performed in absence of real world navigation. It is thus problematic to claim that the perspective aspects of the display would be conducive to mental integration with the user's view of real world because testing did not occur in a driving environment. Furthermore, the favorable results for the perspective display may only reflect the additional mental rotation required by the study task when using the map display. A third experiment in the study replaced the global coordinate directions used in the map display with user centered directions. This experiment did not yield statistically significant differences between perspective and map displays. This suggests that the coordinate system (either global or user centered) had the most impact on user performance. Rather than reflecting and complementing the user's perspective view of the world, the perspective viewpoint in this display may have only served to highlight the arrow indicating the next turn. Perspective distortion increases the screen size of objects closer to the user. These issues suggest that Spoerri's study is inconclusive with respect to the use of perspective viewpoints for a map.

Another set of findings supporting a perspective viewpoint comes from another study concerning navigational checking. Schreiber et al. [126] examined the effect of electronic maps with varying rotation angle, elevation angle, and zoom characteristics on the navigational checking task. Rotation angle corresponds to map orientation, while elevation angle measures the downward looking angle of a perspective view. A 90 degree elevation angle yields a top-down view, while lesser angles yield various perspective views. Zoom describes the scale and field of view by the electronic map. Study participants examined simulated forward views out of the cockpit and compared these views with electronic maps of various view configurations.

Schreiber's studies determined that the elevation angle discrepancy between the map and the user's view of the world should be minimized. For example, a pilot who is gazing out of an aircraft cockpit and at the ground with a 30 degree down angle should be using an electronic map with a perspective view rendered with a 30 degree down angle. This result supports a map with a perspective viewpoint since it would best match a wearable computer user's view of the world. The study also replicated results supporting forward-up alignment for maps. The findings for map zoom levels was somewhat complex due to an interaction between zoom and elevation angle. Implications of map zoom will be discussed later in this chapter.

One study involving wearable computers and navigation aids has examined the question of top-down versus perspective viewpoints, and is of potentially great interest for designers of a spatial cognition aid. Walkmap [78], a wearable computer based navigation guide, was developed at the Nokia Research Center. Walkmap used a two dimensional map that could be rendered from a top-down viewpoint or a perspective viewpoint. The authors performed a study involving a navigation task to determine which viewpoint would lead to better performance.

The authors found that the perspective map led to slower completion of their navigation course. Participants commented that the top-down map was easier to use than the perspective map. The authors concluded that the perspective viewpoint was fit for certain navigational tasks, such as exploration, rather than the wayfinding task that was used. However, this conclusion was based on subjective comments made by the study participants, who had only used the wearable for navigation, and not for exploration. No objective data concerning exploration performance was collected. Furthermore, there were some issues of concern with the study's experimental design.

Some of the participants in the Walkmap study knew the area where the study was conducted, while others were not familiar at all. Familiarity with the area may influence the ability of the participant to understand and use a map of the area. The participants all used a top-down map first, then used the perspective map. This can lead to order effects such as learning or fatigue that can change performance on successive tasks. No details were given concerning whether the navigation course varied or stayed the same between the top-down map and perspective map trials. Learning effects could occur if the same course was used. If different courses were used, randomization would be necessary since one course may require better map reading or wayfinding skills, or have terrain that is more difficult to traverse. Furthermore, the measurements used seem rather coarse and may not have revealed much about the accuracy or speed of the map reading and decision making process. Course completion times were normalized for individual differences in speed. However, these completion times may not have a strong relationship with cognitive load or the amount of time used in understanding the map and making route decisions. The error metric in the study only measured whether the user reached each of the designated targets. Distance from the targets was not analyzed. No metric, other than speed, was used to compare the quality of the chosen route with the optimal route.

While some work suggests a perspective display is appropriate, it is important to understand the results of these studies in the context of user tasks and user goals. Previous work has shown that map orientation can be sensitive to user tasks. For example, Harwood and Wickens [50], in a study of helicopter navigation tasks, saw wayfinding performance was highest for a north-up map, but forward-up maps better supported reorientation tasks in which pilots had to make course corrections after being placed off course. Their results also suggested that subcomponents of particular tasks may also require different map orientations. It is possible that viewpoint is similarly task or even subtask sensitive.

In the task domain of navigation and wayfinding, Darken has identified four basic navigational tasks [32, 31].

Naïve Search: The individual has no prior knowledge of the target's location, nor does the target appear on the map. An exhaustive search must be performed.

Primed Search: The individual knows the location of the target, but the target does not appear on the map.

Targeted Search: The target appears on the map. The map can be used to guide a search.

Exploration: Any wayfinding task that does not have a target.

In one study, Darken examined the three search tasks in virtual environments depicting urban and ocean environments [31]. Study participants used forward-up maps or north-up maps while performing the three different search types. His results suggested that for targeted searches, a forward-up map is most appropriate since participants had to make navigation decisions, such as turning left or right turns, in a ego (self-centric) reference frame. For primed search or naïve search where a world centered reference frame is useful, a north aligned map is more appropriate. While Darken did not explicitly examine exploration tasks, he argued that exploration does play a role in search. However, further consideration of the exploration task is necessary in order to follow the design lesson promoted by Darken's results: match map presentation to the user's task.

A wearable computer based spatial cognition aid should help a user understand and learn the structure of the surrounding environment. This is clearly an exploration task since there is no specified target. However, the tasks involved in previously mentioned studies are usually wayfinding tasks involving some type of target. For example, the "You are here" maps studied by Levine often support targeted searches. These maps may also be used in primed searches when a user identifies objects on the map that are near their desired target. The navigational checking task studied in Aretz and Wickens and by Schreiber et al. is a subtask of aircraft navigation, where flight paths and destinations are often planned and known in advance. Most electronic wayfinding aids are used in targeted searches. Wayfinding aids will either display the location the target such as in Walkmap, or directions that lead the user to that target, such as in Spoerri's guidance display.

Devices supporting a targeted search task will have different requirements than devices supporting exploration. The ultimate requirement for supporting targeted search will be the traversal of a efficient path from the user's current position to the target location. Subtasks may include locating one's own position, finding distance and direction to the target, and planning a route that avoids obstacles in between. Many of these tasks can be assigned to the computer, so potentially, very little information about the structure of the environment must be communicated to the user. Navigation aids like "map-in-the-hat" [149] represent this philosophy. These aids only indicate direction and distance to targets. Other aids like Spoerri's guidance display [135] provide a sequence of directions to the user, communicating a route traversal procedure. In contrast, other aids like Walkmap [78] used map based displays and provide more information about the environment for route planning.

A device that supports exploration and spatial learning should emphasize communication of environmental information to the user. It would be inappropriate to provide direction and distance to objects, or sequences of turns. It should communicate the spatial relations of objects in the user's view of the real world. For such tasks, a perspective map may be inappropriate. A map rendered from a top-down viewpoint may be better. A perspective viewpoint employs distortions that shrink distances and object dimensions based on distance from the viewpoint. Spatial relationships in the map can become harder to perceive. Wickens et al. [165] showed that perspective navigation displays suffered in comparison to 2D displays when precisely locating objects. Furthermore, for maps including 3D representations of terrain and buildings, occlusion can hide some of the objects and the spatial relationships in the scene. While a perspective viewpoint seems unlikely to be the best configuration, an experimental study of these viewpoints in the context of a wearable computer based spatial cognition aid should be performed.

Even after consulting the literature, the issue of map orientation remains somewhat unresolved. It may be easier to memorize a north-up map which has consistency and stability. However, the users of a wearable computer based spatial cognition aid will be viewing the map while exploring. Relating such a north-up map to the environment would require mental rotation. Exploring users may be quite unfamiliar with the region and may be less able to determine matching features in the map and the world. They would not be able to determine the appropriate angle for mental rotation. Furthermore, some evidence from aviation navigation suggests that the workload of mental rotation while flying may negate the memorization benefits of a north-up map [165]. This issue of map orientation in a wearable computer based spatial cognition aid bears further study.

6.3 Series 1: An Exploratory Study

The purpose of this first study was to perform a broad exploration of information presentations that could be used by wearable computer based spatial cognition aids. These different presentations were evaluated by letting different groups of users travel an unfamiliar area while using different presentations. The mental map of the users in each group was then examined. Any trends towards better mental maps revealed more effective information presentations. In this study, the group of information presentations under consideration were created by varying two important factors: viewpoint and orientation.

The viewpoint factor described the vantage point for the overview map. It had two levels: top-down and perspective. The top-down viewpoint was centered 700 meters above the user and was aimed straight down. By contrast, the perspective viewpoint was located 350 meters above and 200 meters behind the user. This placed the perspective viewpoint approximately 400 meters from the user's location and with a 60 degree down angle (see Figure 34). Both viewpoints used a horizontal field of view of approximately 60 degrees.

The second factor was orientation, which referred to how the overview map was aligned. There were three levels: body oriented, head oriented, and north oriented. The body oriented map used a sensor mounted on the user's body (right shoulder), causing the map's alignment to largely reflect the user's travel direction. The head oriented map used a head mounted sensor, so the overview map's alignment reflected the user's gaze direction. The north oriented map maintained a north-up alignment, regardless of the direction the user was facing or traveling.

The experimental groups reflected the crossing of these two factors, with two exceptions. The experiment included a control group that was not provided with any form of overview map. This provided a group of unassisted users as a baseline for comparison. The second exception was the omission of a group with a perspective viewpoint and a north-up orientation. This configuration would have been awkward and confusing. Users would not have been able to perceive their direction of travel from the map. Due to these drawbacks, this condition was omitted.

Table 4: Experimental groups used in the first spatial cognition study.

Group	Map	Viewpoint	Orientation	Notes
1	No	N/A	N/A	Control group, no wearable
2	Yes	Top-down	Body	Tracker on body
3	Yes	Top-down	Head	Tracker on head
4	Yes	Top-down	North	North aligned display
5	Yes	Perspective	Body	Tracker on body
6	Yes	Perspective	Head	Tracker on head

6.3.1 Method

6.3.1.1 Participants

Participants were recruited from geography classes at Georgia State University. This satisfied the requirement that participants be unfamiliar with the Georgia Tech campus. It would be impossible

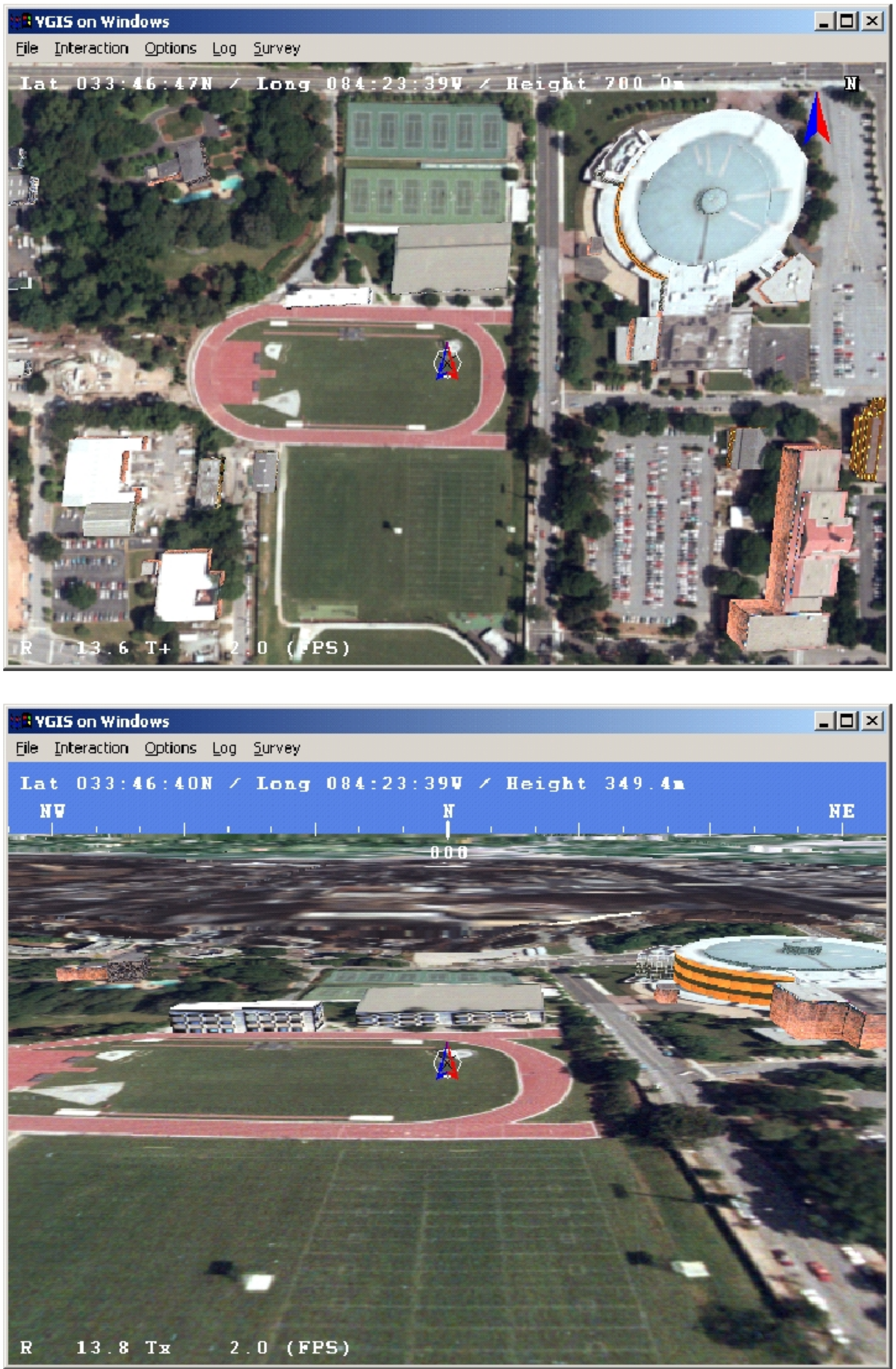


Figure 34: Examples of top-down (above) and perspective (below) viewpoints used in the first study of spatial cognition.

to evaluate learning if participants already knew the area. Participants were also required to have binocular vision (vision in both eyes) in order to effectively use an eyeglass mounted display. Participants were compensated for their time and effort through extra credit in their geography course.

Participants in the study were given a questionnaire to capture demographic information such as age, gender, occupation, level and type of education, and other characteristics that may be correlated with spatial skills. Psychological factor tests for visual memory and spatial orientation ability were also given [35].

6.3.1.2 Apparatus

Figure 35: Wearable computer used in the spatial cognition studies.

Hardware: The apparatus used in the study is shown in Figures 35 and 36. An SV-9 eyeglass mounted display manufactured by MicroOptical Corporation were used in both experiments to display the overview maps. This display provides a 640x480, 24 bit color image at 60Hz. It was attached to the participant's eyeglasses or to a set of eyeglass frames without lenses.

A 2GHz Pentium 4 laptop ran the map visualization software and provided the images for the eyeglass mounted display. The laptop also gathered orientation data from a head mounted or

1. Eyeglass mounted display, 2. Display interface and battery, 3. Laptop computer, 4. GPS, 5. GPS battery, 6. GPS battery voltage converter, 7. Orientation sensor on hat, 8. Orientation sensor battery

Figure 36: Components of the wearable computer used in the spatial cognition studies.

body mounted IntertiaCube2. A shoulder mounted Garmin GPS unit provided position data to the laptop.

A backpack was used to carry the laptop, batteries, GPS, and the video interface box for the MicroOptical display. The IntertiaCube2 orientation tracker was either attached to a shoulder of the backpack, or to a baseball cap, depending on the orientation condition.

Software: VGIS [69, 82], a whole Earth 3D terrain visualization system, was used to render the overview map in the eyeglass mounted displays. VGIS uses 3D rendering and level of detail algorithms to provide an interactive environment for displaying 3D terrain, 3D buildings, and a variety of other geospatial data.

Three modifications to VGIS were required for these experiments. First, program code was added to gather latitude and longitude from the GPS unit. Second, a perspective viewpoint was enabled which placed the viewpoint above and behind the GPS reported location. An overhead viewpoint was already available in VGIS. The final modification was the addition of code to gather yaw angle from the InertiaCube2 orientation tracker.

Interactive controls to adjust factors such as zoom or the elevation angle used in the perspective display were not made available in the software provided to study participants. While such controls could conceivably improve performance, more user training would be necessary. Furthermore, participant performance would reflect the participants ability to manipulate the control effectively and their ability to devise strategies to aid their own performance. This could yield far more variation among participants and obscure effects of the orientation and viewpoint factors.

Data Collection Apparatus: The data collection apparatus included a demographic questionnaire, two psychological factor tests, a photograph location test, and an exit questionnaire. These documents (excluding the psychological factor tests) are available in Appendix C.

The demographic questionnaire was a set of questions concerning age, gender, occupation, level and type of education, and other characteristics that may be correlated with spatial abilities.

Two psychological factor tests were used, Visual Memory (MV) and Spatial Orientation (S), which are standardized tests from the Educational Testing Service (ETS) [35]. They took about 30-45 minutes altogether to complete. A stop watch was used for proper timing.

The photograph location test consisted of 30 photographed scenes from the Georgia Tech campus. Twenty of the photographs were of scenes and buildings from the training route, while the remainder were taken outside the training route. The participants first determined whether the photograph was from the training route, and if it was, they marked the photograph's location on a map and labeled it with the photograph's number. The photographs were taken in advance, but during the same times of day as the experimental sessions.

The exit questionnaire was used to learn about what the participant thought of the experiment and gain some insights into what was difficult in the task and how the system might be improved.

6.3.1.3 Procedure

Participants were recruited from geography classes at Georgia State. Students were asked to sign up for a particular 2 hour session on a particular day. Email addresses and phone numbers were also collected so that students could be reminded of their scheduled session. A web page providing a map for parking and the study location was provided. This map did not show any details about the area where the study was conducted. Outdoor experiment sessions took place in the early morning around sunrise (7AM to 9AM) or early evening just before and after sunset (approximately 5PM to 9PM) to avoid the most intense sunlight which might interfere with the eyeglass mounted display. Fortunately, good weather was enjoyed during the study. Good weather was important to limit equipment exposure to moisture and maintain similar light conditions between participants.

Upon arrival, the participant was given a consent form. After answering any questions the participant might have, she was asked to sign the consent form. She was then given the demographic questionnaire and asked to fill it out. Next, the participant was given the two timed psychology factor tests. For some participants, the psychology factor tests were delayed until the end of the experiment, in order to complete the outdoor part of the experiment during favorable light conditions.

Participants were randomly assigned to an experimental group. As appropriate for the experimental group, participants were fitted with the eyeglass mounted display, the baseball cap mounted InertiaCube2, and the backpack containing a laptop computer and GPS. Proper fitting of the eyeglass mounted display was ensured at this time. The participants were also advised about safe use of the display. The participants were then led to the starting point of the outdoor training route. While software and hardware was initialized, the photograph location test was described in detail. The participants were also told that they would need to recognize and locate scenes from the route. Information about the screen display was also given. For example, the participants were told what type of display they were using, how it worked, and that the center target icon showed their approximate location (see Figure 34).

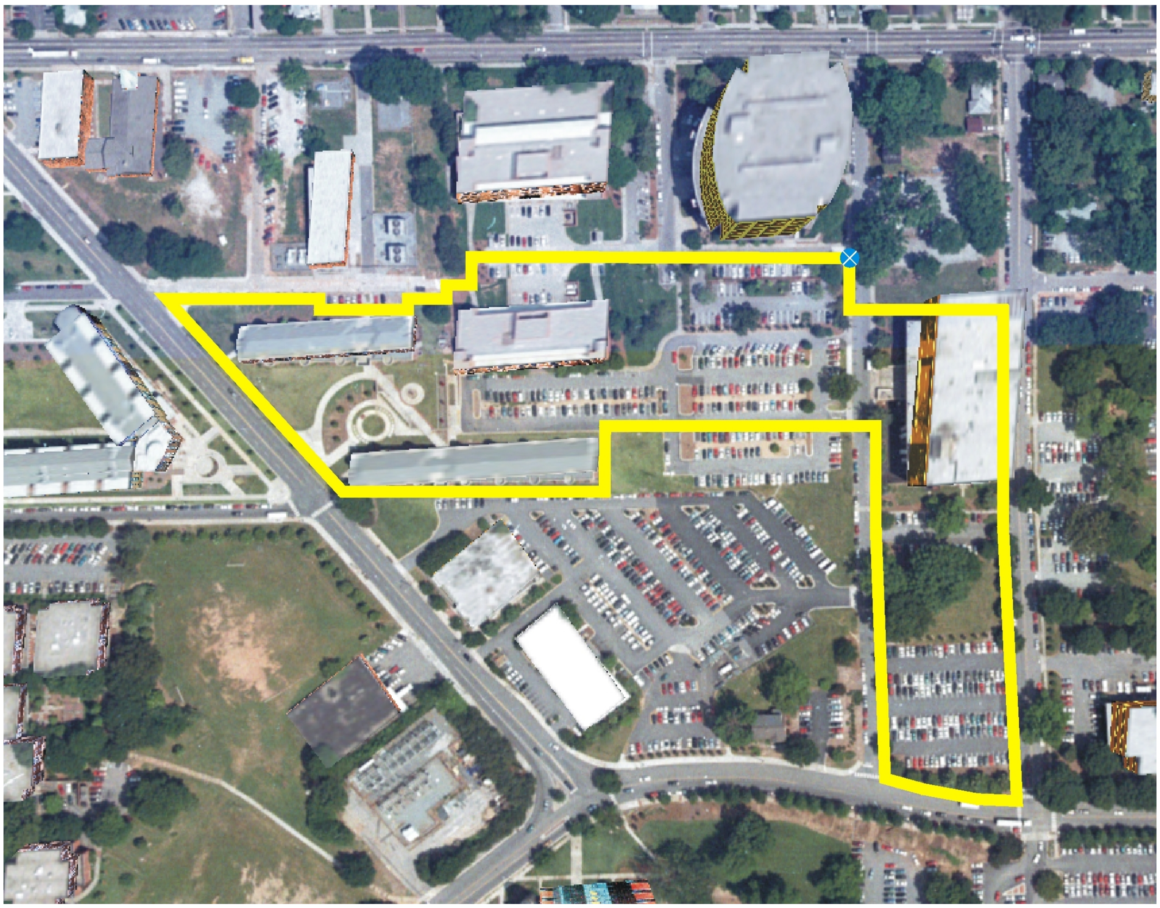


Figure 37: Route taken by participants in the outdoor experiment. The circle with an 'X' denotes the starting and ending point.

The experiment's training task consisted of two identical circuits of a predetermined route on the Georgia Tech campus (see Figure 37). Participants followed the experimenter (the author in all sessions for consistency), but only limited verbal directions were given as to avoid affecting the participants' performance. For example, the experimenter did not refer to landmarks and used gestures rather than directional language (e.x. "left" or "right") to indicate changes in direction. The experimenter consulted a stopwatch and maintained a steady pace to minimize variation in travel time. The total travel time was also recorded. The route was approximately 1.5 miles in total distance (both laps together) yielding a 30-35 minute journey at normal walking pace (around 3 miles per hour).

For safety, in addition to the experimenter, an assistant was assigned the sole task of safeguarding participant safety. The assistant closely followed the participant and was ready to guide the participant around potentially unobserved hazards such as pedestrians, curbs, poles, and traffic. Verbal warnings about stairs and curbs were given. However, no physical guidance was ever necessary during the course of the study. No one fell or failed to notice any hazards.

After the training task, participants were asked to take the photograph location test. For each of the thirty photographs, the participant determined if she saw that scene or building during her travel. If she remembered the scene, she marked an 'x' on a map to denote the location from where she saw the scene, and she labeled the 'x' with the picture's number.

After completing these tests, an exit questionnaire was be given to elicit feedback on the system, the experiment design, and the process.

6.3.2 Results

One issue with this data was the low number of participants per experimental group (Table 5). Ensuring participant attendance was a significant procedural challenge in conducting this experiment. To deal with the low group populations, the data analysis examined one factor at a time, either only viewpoint or only orientation, rather than the effects of both variables at the same time. This had the effect of collapsing experimental groups together.

Under ANOVA, orientation alone did not have a significant effect on recognition errors or location error at the $p < 0.05$ level (see Table 6). Recognition errors indicated the number of incorrectly

Table 5: Experimental group populations for the first spatial cognition study.

Group	Map	Viewpoint	Orientation	Notes	Population
1	No	N/A	N/A	Control group, no wearable	15
2	Yes	Top-down	Body	Tracker on body	5
3	Yes	Top-down	Head	Tracker on head	6
4	Yes	Top-down	North	North aligned display	5
5	Yes	Perspective	Body	Tracker on body	5
6	Yes	Perspective	Head	Tracker on head	5

identified photographs. Location error was measured in 50ths of an inch on the paper map marked by the participant.

However, viewpoint did have a significant effect on photograph recognition (ANOVA, $p = 0.032$). These results are shown in Table 7. Participants with a perspective viewpoint missed far more photographs than the control group (Tukey HSD, $p = 0.034$). Participants with the top-down viewpoint did not miss significantly more photographs than the control group (Tukey HSD, $p = 0.914$). Adding mental rotation and visual memory covariates reduced the significance of the effect (ANCOVA, $p = 0.079$). However, the effect was still notable.

Table 6: There were no significant differences for orientation in the first spatial cognition study

Orientation	Mean Number of Recognition Errors*	Std. Dev.	Mean Location Error† (50ths of an inch)	Std. Dev.	Population
No Map	7.47	2.973	7.36	6.358	15
North	7.20	2.950	5.65	2.272	5
Body	8.70	2.111	7.03	4.918	10
Head	9.27	1.794	5.44	5.597	11
Total	8.22	2.545	6.59	5.346	41

*ANOVA for the number of recognition errors did not reveal significant differences ($p = 0.229$).
†ANOVA for location error did not reveal significant differences ($p = 0.814$).

Table 7: The number of recognition errors for the perspective viewpoints was significantly more than the control group in the first spatial cognition study

Viewpoint	Mean Number of Recognition Errors*	Std. Dev.	Mean Location Error† (50ths of an inch)	Std. Dev.	Population
No Map	7.47	2.973	7.36	6.358	15
Top-down	7.81	2.105	5.22	3.290	16
*Perspective	10.00	1.700	7.47	6.258	10
Total	8.22	2.545	6.58	5.346	41

*The perspective group had significantly more recognition errors than the no map (control) group, (ANOVA, $p = 0.032$) and (Tukey HSD, $p = 0.94$).
†ANOVA for location error did not reveal significant differences ($p = 0.468$).

A number of subjects commented about the equipment used in the study. Some felt that the system was too heavy, which it was, at approximately 10 lbs. Others commented that the eyeglass mounted display would shake while walking, making it difficult to focus on the display. These comments were not specific to any particular experimental group.

There were some comments specific to the overhead map presentations. Users of the overhead maps did want larger displays, more detail, or the ability to zoom in or out. However, many commented that the overhead maps did help them locate scenes in the photograph test. Some of the comments from the north oriented map group expressed difficulty in correlating the map with the surrounding environment or understanding the direction of travel. One user wanted the ability to at least flip the map upside down and right-side up. Another user acknowledged hardly using the display.

Users of the perspective maps gave comments that were less supportive. Two users commented that the perspective map did help them remember their route. However, some users had difficulty in determining how they were oriented or had difficulty in correlating real buildings with their map. Some users found the viewpoint distracting or confusing and one would have preferred a viewpoint that did not show any terrain behind the user. Another wanted a wider field of view. One user admitted to relying mostly on innate sense of direction.

6.3.3 Discussion

The experiment did show significant differences in recognition errors depending on the map viewpoint used. Users of the perspective viewpoint made far more errors than users who did not use a wearable computer. Most of the recognition errors made in the study were "misses" where a participant failed to recognize a photograph that was part of the route taken. The one likely explanation, also taking account of user comments, is that the perspective view was distracting. With the user's attention drawn to the display, they would have missed some of the scenes along the route.

This distraction can result from the instability of the perspective viewpoint. Instability is one of the problems with this type of display and was also noticed in the Walkmap project [78]. Since the map viewpoint is tethered to a long vector attached to the user's position, small changes in the user's position and especially heading can create large changes in the map image. Filtering can smooth out these changes, but due to the geometric construction of this view, they are unavoidable. Furthermore, characteristics such as perspective distortion and occlusion also make it more difficult to understand the spatial relations between objects in this view. It is very possible that a user trying to understand a complex, unstable view would be distracted from noticing and learning their surroundings.

The quality of the virtual model of the environment may also have been a cause of distraction in perspective viewpoint. Inaccuracies and simplications in the model are much less apparent in a top-down viewpoint since users are less able to see terrain elevations and the sides of buildings. With the perspective view, users may have been more able to notice these imperfections. The imperfections in the model may have been distracting, particularly if the user was comparing the model to the surrounding environment. The use of a more veridical model might have lessened the distraction associated with the perspective viewpoint.

While the objective performance measures did not all return significant results, it is also important to note that differences in spatial ability between individuals can be large, yielding a naturally large variation in performance. Map presentation may cause performance differences, but they may be small, difficult to measure, and may be overwhelmed by the large variation caused by spatial ability. This can also explain why orientation did not yield significant performance differences.

There is not much operational difference between placing an orientation sensor on the body or on the head. Individuals mostly maintain head alignment with the body's direction of travel. The north aligned orientation condition was also not significantly better, perhaps because its use required a great deal of mental rotation, adding to the user's cognitive load. Also, users may have had difficulty in accurately determining the amount of rotation needed, since they were unfamiliar with the environment.

However, user comments can play a role, if considered carefully, in guiding further studies. Learning the surroundings is a rather subtle goal and participants can easily become frustrated or disengaged if the display presents any difficulty. In this respect, user acceptance can be a very strict test of the different presentations. In the north-up alignment, user comments reveal drawbacks to the north-up orientation. Users did have difficulty in reconciling their travel direction with a north-up map. This difficulty may have prompted one user to rely on innate sense of direction rather than use the display. Since other work has suggested that mental rotation can interfere with spatial learning [165], the north-up display seems less compelling.

Unfortunately, since no significant differences in location error were seen, the study could not clearly demonstrate that any map configuration on a wearable computer could improve the mental maps of the participants. However, the perspective display did interfere with recognition. In light of user comments and recognition errors, a top-down, forward-up map seems the most promising choice. Such a map would be less distracting and allow the user to more easily integrate their view of the world with their map.

6.4 Series 2: A Second Investigation and Refinement

A second study was planned and performed with the purpose of closely examining the presentation with the top-down viewpoint and the head orientation. By focusing on only a control group and a single experimental group, each group would receive more participants, yielding a better statistical sample. The head orientation was chosen for this experiment since the body oriented map and head oriented map had indistinguishable performance and the head oriented map would more closely correlate with the user's view of the world.

This study was also conducted in two phases. The first phase used the same top-down, head oriented map that was used in the previous study. Preliminary analysis after the first two weeks of conducting the study showed no significant difference with the map. These preliminary results caused several changes to be made for the second phase of the experiment. Modifications were then made to the map presentation to account for the infrequent manner in which users attend to the display. These modifications proved successful, allowing users of the top-down, head oriented map to better learn the structure of the environment than those who did not have a wearable computer.

6.4.1 Design Issues

An important design consideration in wearable computing is the division of user attention. While wearable computers are continuously available, they often should not be the focus of the user's attention. The user may be conversing with others, navigating across terrain, or performing a maintenance task. It is important that the wearable computer does not distract the user in a manner that is unsafe in critical situations, or embarrassing in social situations. This is a very important distinguishing characteristic between wearable computer applications and desktop computer applications.

The wearable computer should not be like a spoiled child who demands all of the user's attention at inopportune moments. A good model for a wearable computer is the "good English butler" who hovers in the periphery, unnoticed, until assistance is needed. As such, wearable computer applications should be designed to reflect the limited availability of the user's attention.

In a spatial learning situation, user attention is divided between the surrounding world and the wearable computer display. Some attention is required to avoid obstacles and maintain a heading. Further attention is required to perceive and remember the scenes from the user's route. These demands cause the user to look infrequently at the wearable computer display. Between these infrequent glances, the map may have moved and rotated a great deal. It is then difficult to correlate these different views of the map. The user cannot perceive the overall layout of the map. The user is then less able to construct a mental map that integrates both the map and the user's views of the real world. Participants in phase 1 of the study may have been experiencing this difficulty in correlation.

A good spatial cognition aid should assist the user in correlating these different glances at the display. Some continuity between glances should be preserved. While a north-up map does provide stability that may yield this kind of continuity, the north-up map requires mental rotation to correlate the map with the surrounding world. Navigation during map use creates a demand for constant mental rotation. This mental rotation may interfere with spatial learning [165].

In phase 2, two modifications were made to the top-down, head oriented display (see Figure 38). First, the map view was expanded to cover a wider area of the map. This reduced the changes in the map between glances at the display. This also ensured that the set of landmarks shown on the map remained fairly stable and constant. For example, landmarks near the starting point remained on the map throughout the user's travel. Second, the user's trail was automatically marked as the user's journey progressed. This was done to allow the user to see the shape of their own route and gauge their progress between glances. Route shape could remind the user of their sequence of turns and allow the user to better correlate their experience with the layout of the environment. Furthermore, the progress indication could allow users to concentrate on memorizing a sequence of real world scenes. They could then glance at the display, easily perceive the trail markers showing the latest distance traveled, and correlate the sequence of scenes with that new segment. Without the trail markers, users would have to remember their previous location on the map, consider their current map location, and then determine their progress, adding additional memory and mental calculation tasks. If considered in light of distributed cognition theory, the route markers support cognition in the world, allowing the user to offload some memory demands. In effect, the marked route could act as a thread in time and distance, connecting views of the map and views of the world.

6.4.2 Method

6.4.2.1 Participants

Participants were recruited and compensated in the same fashion as the previous study. An entirely new set of students were recruited from the next session of the introductory geography course at Georgia State University.

A number of techniques were employed to insure better participant attendance. Participants were sent reminder messages by email several days in advance. They were also telephoned the day before their session. As before, extra credit was given for participation, but participants could also lose credit for failing to attend without prior notice. These factors improved participant attendance a great deal.

Participants were required to have binocular vision for wearable computer display use, and were required to be unfamiliar with the Georgia Tech campus. Questionnaires gathered demographic information and psychological factor tests [35] were given to determine memory and mental rotation skills.

6.4.2.2 Apparatus

The data collection materials in this study were the same as in the previous study. These included a demographic questionnaire, two psychological factor tests, a photograph location test, and an exit questionnaire. See Ekstrom [35] for the psychological factor tests, and Appendix C for the other test materials. Seasonal changes between fall and spring required new photographs for the photograph location test. New photographs were taken from the same locations and orientations as the old photographs. Both sets of photographs are included in Appendix C.

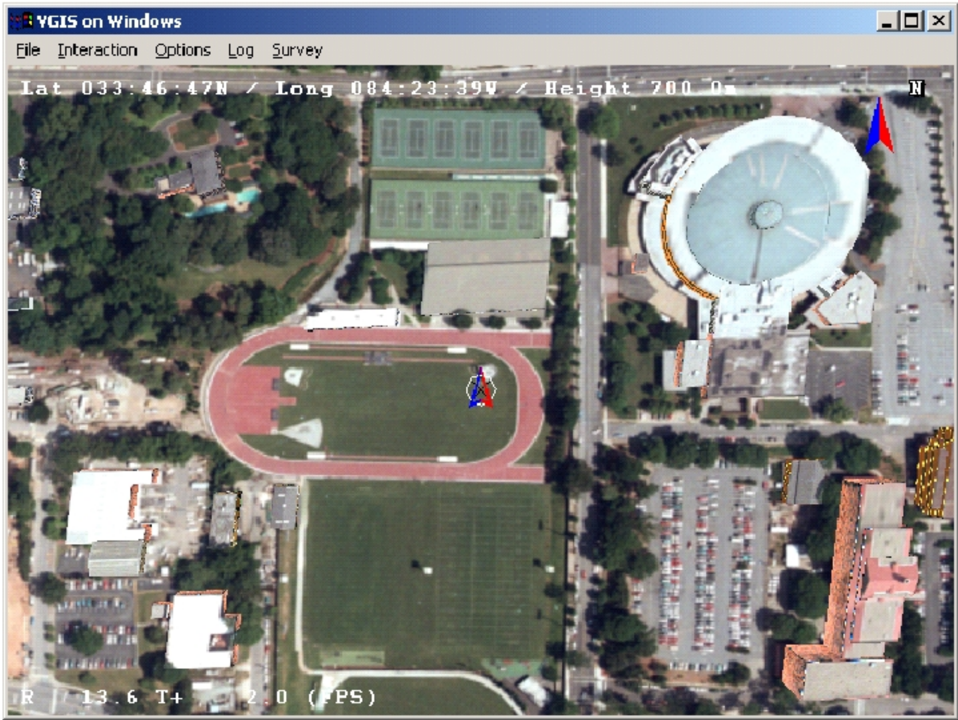
The hardware apparatus remained the same as in the previous study (see Figures 35 and 36).

The software used in this study was very similar to the software in the previous study. VGIS was again used for rendering the map and gathering position and orientation information from the tracking devices. However, the configuration of the view changed in phase 2 of this study.

Phase 1 of the study used only one of the various map presentations from the previous study, the top-down head oriented view. The viewpoint was located 700 meters above the user's location and the map was oriented to align the top of the map with the user's gaze direction. The viewpoint had a 60 degree horizontal field of view.

Phase 2 used a modified version of the top-down, head oriented display (see Figure 38). In this version, the viewpoint was moved to 1000 meters above the user's location, yielding a view of a larger area. The map was also oriented with the user's gaze direction. Additionally, the user's trail was displayed with a series of small white markers. A new marker was created every 15 seconds at the user's current position.

One additional change was made to the VGIS software. A logging function was added to VGIS that recorded user position, travel direction, and head orientation every 2 seconds. This can help determine how user head movements are affected by a wearable computer display. Data for comparison was acquired from some participants in the control condition who were asked to carry the



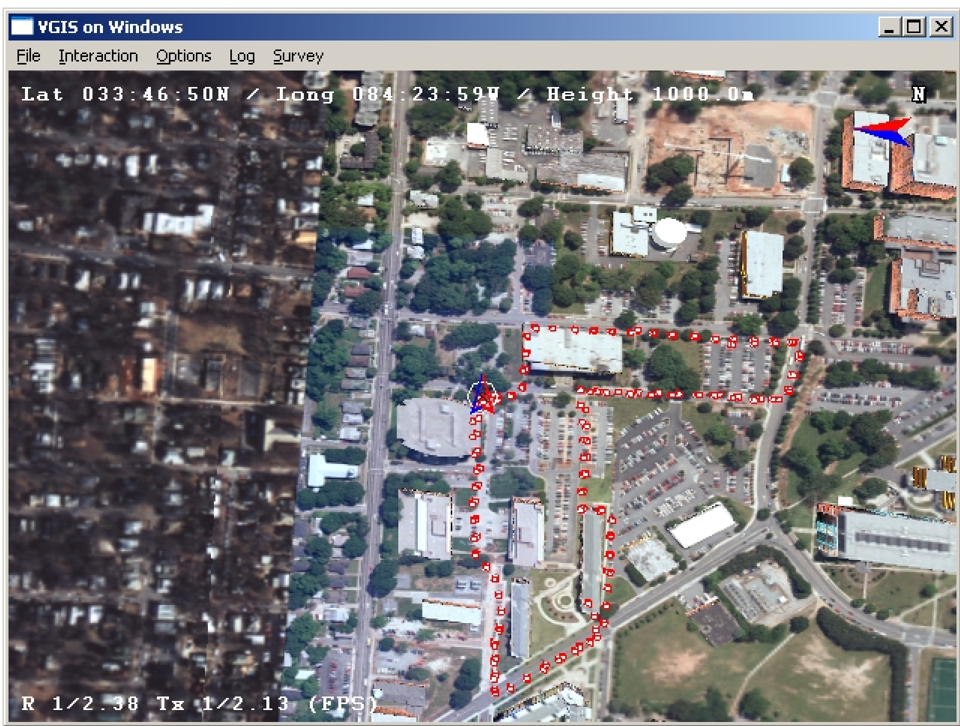


Figure 38: Examples of top-down (above) and modified top-down (below) viewpoints.

wearable computer (without a display). Unfortunately, data dropouts in the logging did not allow for samples that were large enough for analysis. The GPS provided continuous location information, but often failed to provide direction of travel information for comparison with the head direction reported by the orientation sensor. Furthermore, this direction of travel is determined by examining how the user's location changes over time. Since an individual GPS location fix can be inaccurate, several location fixes are averaged together. This can make the reported direction of travel lag behind the user's true direction of travel. A better approach would be to use a second orientation sensor, perhaps mounted on the user's shoulder, could be used with a head mounted orientation sensor to determine head movement.

6.4.3 Procedure

This study utilized the same procedures as the previous experiment, however, participants were assigned to one of only two groups. In phase 1, participants were assigned to either a control condition without a wearable computer, or an experimental condition with a head oriented, top-down map display. In phase two, participants were assigned to either the control condition, or the modified head oriented, top-down map display.

6.4.4 Results

As mentioned previously, phase 1 of the study did not show any significant performance differences between the control group and experimental group (Table 8). Recognition errors indicated the number of incorrectly identified photographs. Location error was measured in 50ths of an inch on the paper map marked by the participant. An ANOVA statistical test of the recognition errors resulted in a p value of 0.852, which is far above the chosen $p < 0.05$ significance threshold. An ANOVA test of location error returned a p value of 0.196, also above the significance threshold.

ANCOVA tests were also performed to determine if significant performance differences would emerge after mental rotation and visual memory test scores were used to account for some performance variation. ANCOVA also did not reveal significant performance differences.

In Phase 1, more participants were run in the control group than in the wearable computer group. A number of these control group participants had head direction and position logged by the wearable computer (without using the map display). This inflated the number of control group

Table 8: No significant differences found for recognition or location error in phase 1 of the second spatial cognition study

Group	Mean Number of Recognition Errors*	Std. Dev.	Mean Location Error† (50ths of an inch)	Std. Dev.	Population
Control	5.30	3.582	4.52	3.986	27
Experimental	5.50	2.624	6.46	5.323	14
Total	5.37	3.254	5.18	4.517	41

*ANOVA for the number of recognition errors did not reveal significant differences ($p = 0.852$).
†ANOVA for location error did not reveal significant differences ($p = 0.196$).

participants since there was only one wearable computer and participants were often run in pairs. Unfortunately, due to data dropouts as previously discuessed, an insufficient amount of data was collected for analysis.

The results of the second phase show some performance differences in location accuracy (Table 9. An ANOVA of the location error metric returns ($p = 0.090$). However, an ANCOVA, accounting for mental rotation and visual memory scores, yields ($p = 0.015$), showing a significant difference at the $p < 0.05$ level. The location error metric is based on the average distance between the true location of the photographs and the participant's responses. Participants who used the wearable computer with the modified map display had a lower mean location error. They were able to locate the photographs more accurately than participants who did not use the wearable computer.

Phase 2 did not indicate any significant differences between groups for recognition errors. This means that the study could not detect any significant distraction effects from the wearable computer.

6.4.5 Discussion

While Phase 1 did not detect any distraction effects such as those seen with the perspective display in the previous study, neither could Phase 1 detect any spatial cognition advantages for users of the wearable computer.

The modifications made to the display for Phase 2 (see Figure 38) allowed the users to effectively understand and use the map. Since wearable computer users must split their visual attention

Table 9: Significant differences in location error were found in phase 2 of the second spatial cognition study

Group	Mean Number of Recognition Errors*	Std. Dev.	Mean Location Error† (50ths of an inch)	Std. Dev.	Adj. Mean Location Error	Population
Control	5.85	2.375	6.94	4.912	7.24	13
Modified Display	5.31	3.535	4.36	2.887	4.12	16
Total	5.55	3.031	5.52	4.062	5.68	29

*ANCOVA for the number of recognition errors did not reveal significant differences ($p = 0.885$).
†A significant difference was seen for ANCOVA adjusted means of location error ($p = 0.015$).

between the world around them and the wearable computer, it can be difficult for users to follow their progress on the map and learn the layout of the environment. The viewpoint was adjusted so the map covered a much larger area. This presented a more consistent set of landmarks to the user. The display also laid down trail markers, indicating where the user had been. These modifications proved to be successful. Participants who used the wearable computer in Phase 2 located photographs more accurately than participants in the control group.

6.5 Summary

This chapter discussed two studies that were conducted to explore various design issues in wearable computer based spatial cognition aids. The first study examined a broad range of map orientations and viewpoints. The second study focused on the top-down, head oriented map presentations. The second study also addressed an important design issue for wearable computing: the division of user attention.

These studies have demonstrated two important ideas. First, a wearable computer, when appropriately configured, can help an individual learn the structure of the environment better than an unassisted individual. This shows that a wearable computer can be used as a platform for an effective spatial cognition aid. While many researchers have investigated the use of wearable computers for a variety of outdoor applications, those investigations have typically focused on navigation aids, tourist guides, and surveying aids. The results of the studies in this chapter demonstrate that spatial cognition and spatial learning are viable applications for wearable computers.

Second, these studies have identified and explored some of the important design issues for wearable computer based spatial cognition aids. Some important design lessons have emerged. The studies suggested that a perspective viewpoint may be distracting for users. A spatial cognition aid should provide a top-down viewpoint, which better matches the survey knowledge that should be taught to the user. Finally, the spatial cognition aid should account for divided visual attention. Some successful techniques employed in these studies include providing a stable and consistent set of landmarks and indicating the user's path with trail markers. The use of the trail markers also demonstrates that notion of offloading cognition from the user's mind onto the wearable computer.

CHAPTER VII

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

It can often be difficult for humans to understand their surroundings for many reasons. We typically do not have a vantage point that allows us to view the environment from above and in its entirety. These environments are also very large and complex.

This dissertation has examined the use of wearable computers as a platform for a spatial cognition aid. A spatial cognition aid is a tool for helping individuals perceive, understand, and remember the layout of the surrounding environment. While a map has been a common spatial cognition aid for quite some time, it is important to explore new media, such as mobile and wearable computers. This dissertation did not try to compare ink and paper maps and wearable computer based spatial cognition aids because this is not a useful comparison. Maps and wearable computers are different in many ways. Dynamic data can not be presented on a conventional map, while wearables can download new updates, customize the presentation of information, and locate the user using GPS and other technologies. However, maps have very high print resolution and low cost. It is very easy to collaborate and consult with others over the map. They both have a place in human spatial behavior. It is important to explore, develop, and validate the new tool, in his case, the wearable computer based spatial cognition aid. After doing so, the new tool can be a useful and well understood addition to the human tool set.

This dissertation has examined the building blocks of a wearable computer based spatial cognition aid by examining a relationship mediation model for wearable computer applications. The model suggested three relationships are important for a wearable computer based spatial cognition aid. The wearable to environment relationship, the user to wearable relationship, and the user to environment relationship. The relationship mediation model was proposed in this dissertation as a general way to define and understand how wearable computer applications participate in various relationships that humans conduct. This model can help designers of other wearable applications consider how their application can and should impact a user's relationships.

To consider the wearable computer to environment relationship, the dissertation focused on an infrastructure for distributing location based data. In this domain, scalability is of great concern. However, it must also be easy to bring new data services into the infrastructure. This system sought to serve both goals by using geographic distribution and a very simple indexing framework. The system provided a set of location servers that maintained indexes of users and data servers for particular areas. Wearable computer applications could query a location server to determine the users and data servers that could provide information for a user's region of interest.

For the user to wearable computer relationship, the dissertation examined how users can navigate inside a terrain visualization. The terrain visualization provides a virtual model of the environment, which can show a user the layout of the surroundings. Navigation is important for users who wish to peruse and explore an environment. However, alternative interfaces, such as those based on speech recognition and gesture recognition were examined since standard computer interface devices are not effective in a wearable computer environment. While the gesture interface was not very effective, a speech based interface could serve for navigation control for a wearable computer. Interfaces based on isometric joysticks and tilt sensors were also evaluated. Many of these interfaces employed two handed interaction, which can be very expressive for navigation. The evaluation of these candidate interfaces suggested that an aircraft control metaphor yielded very good results.

The most significant contribution of this dissertation came in the consideration of the user to environment relationship. This is the relationship in which the wearable computer mediates and assists the user's perception and understanding of the environment. Few, if any, researchers and developers have considered the wearable computer as a platform for spatial cognition aids. Thus, there is little research in wearable computer that suggests whether a wearable computer can be an effective spatial cognition aid and how to implement such an aid in the first place. The two series of experiments in this dissertation demonstrated that wearable computers can indeed help an individual's spatial cognition. That is, a wearable computer can be an effective assistant for spatial cognition. The studies were also able to show what is an effective presentation for a spatial cognition aid. This presentation rendered environmental data from a top-down perspective and rotated the map to maintain a forward-up alignment. Furthermore, the studies identified that it is important to account for the divided attention of the wearable computer user. The user must contend with information from the wearable computer display as well as the from the environment. The presentation design must help the user understand and follow the changes in the display when the user can only attend at the display infrequently.

In summary, this dissertation makes the following contributions:

- Identification of spatial cognition aids as an important wearable computer application (as opposed to wayfinding aids and tourist guides).
- Demonstration of an effective wearable computer based spatial cognition aid.
- Experimentally derived presentation characteristics for a wearable computer based spatial cognition aid.
- Identification of the need to design for divided user attention.

Other minor contributions of this dissertation of infrastructure or engineering interest include:

- Evaluations of navigation interfaces that employ speech and gesture recognition and two handed interaction. These evaluations yielded design lessons of interest for wearable computer developers.
- A scalable server infrastructure for distributing geospatial information.
- A relationship mediation model that describes how wearable computers participate in relationships of the user.

The work in this dissertation can influence the development of both spatial cognition aids and wayfinding aids. If users of wayfinding aids can develop a good mental model, they could reduce reliance on the wayfinding aid and learn navigate and communicate on their own more effectively. Both spatial cognition aids and wayfinding aids are especially important for military personnel and law enforcement officers. However, the experience of becoming lost, or learning a new area is common to nearly all individuals. It is important to provide mobile and wearable computing applications that are designed according to validated principles such as those found in this dissertation.

Other work in this dissertation can have influences on the larger field of wearable computing. The relationship mediation model can act a guide for wearable computer application developers. It can be a reference point for comparing and classifying other work. As the field of wearable computing matures, models and other guides for software development become increasingly important. The evaluations of navigation interfaces may be useful for other wearable computer applications that involve navigation. This will include both 2D and 3D applications.

7.2 Future Work

Scalability of the spatial cognition aid is a topic that can be further explored. Only a small geographic region was considered in design and evaluation of the aid. Interaction techniques for navigation and zooming can be a part of scaling the aid for larger areas. These techniques should be evaluated for their effect on spatial cognition. With interactive techniques, users may try a number of strategies. Experiments must explore these strategies and consider the additional variation among participants that these strategies bring to a study.

Stevens [142] suggests that the mental map is a hierarchical construct. A spatial cognition aid might be able to exploit this principle for scaling to larger regions. Visual presentation of a spatial cognition aid can reflect this hierarchy. For example, at a neighborhood level, as in the studies presented here, a satellite image may be the most appropriate. It is apparent to suggest that, at the city or county level, imagery of only highways or major roads should be shown. However, perhaps a combination of imagery is needed with more detail around the user's current position, less detail enroute, and more detail around a potential destination. Further studies could determine the appropriate degree of interest functions that match a user's current mental model.

A wearable computer can also be a good platform for studying the formation and extent of a user's current mental model. Some interaction techniques could be developed that allow the user to annotate the spatial cognition aid as they visit new locations. This would be one method by which to link the user's mental map and the system map. Another approach would be to use information about a user's travels to modify the system map in the same fashion that the mental map is expected to change.

APPENDIX A

MULTIMODAL INTERFACE STUDY

The following pages contain copies of materials used during the multimodal interface study. Some of these materials may be reproduced at smaller than original scale to satisfy dissertation formatting.

Title	Number of Pages
Multimodal Interface Study: Consent Form	1
Multimodal Interface Study: Pre-Experiment Questionnaire	1
Multimodal Interface Study: Symbol Familiarity Exercise	1
Multimodal Interface Study: Exocentric Landmark Test	1
Multimodal Interface Study: Mid-Experiment Questionnaire	1
Multimodal Interface Study: Post-Experiment Questionnaire	2
Multimodal Interface Study: Trial Completion Times	1
Multimodal Interface Study: Memory Task Results	1
Multimodal Interface Study: Post-Trial Interface Ratings	1
Multimodal Interface Study: Post-Experiment Interface Rankings	1

Table 10: List of Appended Materials from the Multimodal Interface Study

Cognitive Load for Multimodal Speech and Gesture Interfaces
Informed Consent Form

I agree to participate as a subject in an experiment conducted under the supervision of David Krum. I understand the following issues:

Title of Research Study

The title of this study is "Cognitive Load for Multimodal Speech and Gesture Interfaces."

Principal Investigators

David M Krum	Benga Omoteso	Bill Ribarsky
Principal Investigator	Co-Principal Investigator	Faculty Sponsor
dkrum@cc.gatech.edu	gte414w@prism.gatech.edu	ribarsky@cc.gatech.edu
College of Computing	Georgia Institute of Technology	

Purpose of Research

You are being asked to volunteer for a research study to examine different computer interfaces. These interfaces use speech interfaces, gestures, or a combination of both. A combination of speech and gesture is often called a multimodal interface. The different interfaces are being tested to determine how much mental effort they require. Eligible participants are 18 years or older and fluent in English.

Procedures Used in the Study

Your participation should last approximately one hour. You will first be asked to fill out a questionnaire. This allows us to evaluate how much experience you have had with computers and speech and gesture interfaces. Also, we will give a test for short-term memory. Short-term memory is the ability to remember things for a short period of time.

You will use four different computer interfaces. One interface uses a mouse. A second uses speech recognition. A third uses hand gestures. The fourth interface uses both speech and gesture in combination. This is called a multimodal interface. These interfaces will be used to control a 3D map of the planet earth. Your performance will be timed.

You will see various pictures while using each interface. After using each interface, you will be given a test to see if you can remember which pictures you saw. You will also be given a questionnaire that will ask questions about your experience with the user interface. After you use all four interfaces, you will be given a final questionnaire about your experience.

Foreseeable Risks from the Study

Only minimal risks are expected. Since a 3D display is involved, it is possible that you may experience temporary minor eyestrain, nausea, headache, or dizziness.

Potential Benefits from the Study

We hope that your participation in this study will lead to increased knowledge about multimodal interfaces and lead to better computer interfaces. It also may foster in you a greater understanding of computer interface technology.

Compensation/Costs

You will receive 1 hour of extra credit for you participation in this study. The effect of that extra credit on your course grade is a decision to be made by the instructor. You will receive no financial compensation for your participation.

Alternative Procedures

Alternative opportunities to receive extra credit are available should you choose not to participate in this experiment.

Confidentiality of Records

All information about you, including the questionnaires, computer files, and assessment results will be kept private. A number will identify these records, not your name. Your results will be confidential and will be reported anonymously in any article that this research may generate.

Disclosure Statement

The researchers have no financial interests in the results of the study. However, they may publish the results of the study.

Injury/Adverse Reactions

Any injuries or reactions should be reported to David Krum at (404) 894-6710 or Dr. Bill Ribarsky at (404) 894-6148. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.

Contact Persons

To make inquiries regarding this study, contact David Krum at (404) 894-6710. His office is Centennial Research Building 375. You may also contact Dr. Bill Ribarsky at (404) 894-6148. His office is Centennial Research Building 371.

Voluntary Participation/Withdrawal

Participation in this study is voluntary. You are free to withdraw from participation at any time. Refusal to participate will involve no penalty or loss of benefits to which the subject is otherwise entitled. Under certain circumstances, participants may be withdrawn from the study without their consent if the researcher decides that it is not in their best interest, or if they fail to follow the procedures. If you wish to withdraw from participation, please tell the researcher at any time.

You have rights as a research volunteer. Taking part in this study is completely voluntary. If you do not take part, you will have no penalty. You may stop taking part in this study at any time with no penalty. If you have any questions about your rights as a research volunteer, call or write:

Compliance Manager
Georgia Institute of Technology
Atlanta, Georgia 30332-0420
Voice (404) 894-6942 Fax (404) 385-0864

A copy of this form will be given to you. Your signature below indicates that the researchers have answered all of your questions to your satisfaction and that you consent to volunteer for this study.

______________________________ ________________
Signature of Participant Date

____
Name of Participant (Please Print)

______________________________ ________________
Signature of Investigator Date

Figure 39: Multimodal Interface Study: Consent Form

Cognitive Load for Multimodal Speech and Gesture Interfaces
Pre-Experiment Questionnaire

Subject Number:____________

Gender: Male______ Female______	Age in years: ___________
Do you wear glasses? Yes______ No______	Do you wear contact lenses? Yes______ No______

	Frequently	Sometimes	Seldom	Never
Do you a computer for work? (Word processing, spreadsheets, design, etc.)	4	3	2	1
Do you use a computer for entertainment? (Games, chat, etc.)	4	3	2	1

	Frequently	Sometimes	Seldom	Never
Do you play 3D computer games such as Quake, Unreal, etc?	4	3	2	1
Do you watch movies presented in 3D with 3D glasses?	4	3	2	1
Do you use 3D design software like Autocad or 3D Studio Max?	4	3	2	1
Have you experienced 3D virtual reality with a Head Mounted Display? You wear this on your head, covering your eyes...	4	3	2	1
Have you experienced 3D virtual reality on a large projected screen before?	4	3	2	1

	Frequently	Sometimes	Seldom	Never
Do you use voice recognition software such as DragonDictate or ViaVoice?	4	3	2	1
Have you used voice recognition in a telephone or cell phone?	4	3	2	1
Have you called an airline and used a telephone based voice recognition system?	4	3	2	1
Have you used voice synthesis software? This is a program that talks with a computer generated voice.	4	3	2	1

	Frequently	Sometimes	Seldom	Never
Have you ever used a computer interface that uses hand or arm gestures to control a program?	4	3	2	1
Do you use American Sign Language or some other formal sign language?	4	3	2	1
Do you practice martial arts? (Karate, Kung Fu, Tai Chi, etc.)	4	3	2	1
Do you dance? (Ballet, swing, ballroom, hip hop, etc.)	4	3	2	1
Do you dance? (Ballet, swing, ballroom, hip hop, etc.)	4	3	2	1

Figure 40: Multimodal Interface Study: Pre-Experiment Questionnaire

Comparison of Interfaces for Mobile and Wearable 3D Visualization
Pre-Experiment Symbols

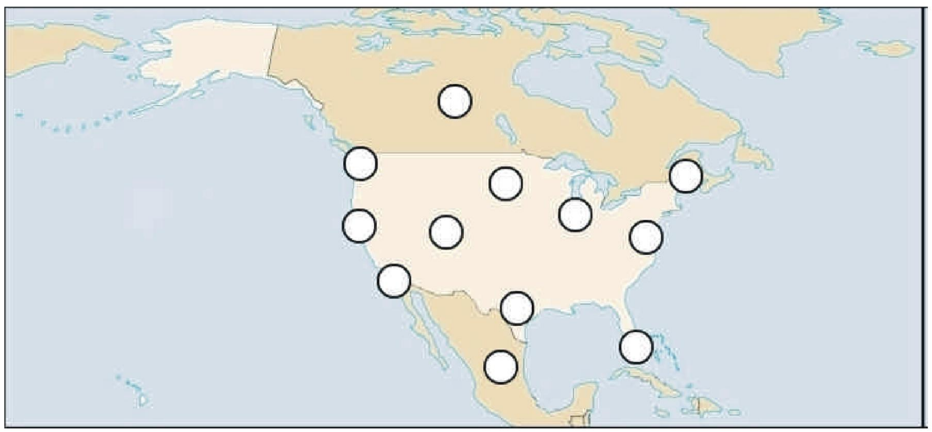
Subject:

Instructions: Come up with a one-word name for each symbol. Write the name below each symbol.

Figure 41: Multimodal Interface Study: Symbol Familiarity Exercise

Subject #	Trial:

1. Find numbers for the symbols you saw. Write the numbers on the map below in the appropriate locations.



2. What order did you see the symbols? Write the numbers below. Put the first symbol you saw first.

First Second Third Fourth

Figure 42: Multimodal Interface Study: Exocentric Landmark Test

Cognitive Load for Multimodal Speech and Gesture Interfaces
Mid-Experiment Questionnaire
Part I

Subject Number: ________			
Mouse	Speech3	Gesture	Multimodal

Instructions: Read the statements and circle your answers.

1. This interface is easy to learn.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

2. This interface is easy to use.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

3. This interface has a lot of errors.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

4. This interface allows fast navigation?

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

5. This interface allows precise navigation?

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

6. It is easy to remember the symbols while using this interface.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

7. Overall, this is an effective interface.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

8. This interface gives me the sensation of being in the map, i.e. I are present and part of the virtual environment.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

9. This interface is comfortable to use.

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

10. I would like to have this interface on my own computer?

Strongly Agree 1	Agree 2	Indifferent 3	Disagree 4	Strongly Disagree 5

What aspects of this interface were helpful to you?

What aspects of this interface were problems for you?

Figure 43: Multimodal Interface Study: Mid-Experiment Questionnaire

Cognitive Load for Multimodal Speech and Gesture Interfaces
Post-Experiment Questionnaire
Part I

Subject Number:______________

Instructions : Rank the interfaces in order. Write the number in the boxes below.

1. Which interface is easiest to learn
(1 - easiest, 4 - hardest)

Mouse	Speech3	Gesture	Multimodal

2. Which interface is easiest to use?
(1 - easiest, 4 - hardest)

Mouse	Speech3	Gesture	Multimodal

3. Which interface had the most errors? Which interface didnít do what you wanted?
(1 - most errors, 4 ñleast errors)

Mouse	Speech3	Gesture	Multimodal

4. Which interface allows the fastest navigation?
(1 - fastest, 4 - slowest)

Mouse	Speech3	Gesture	Multimodal

5. Which interface allows the most precise navigation?
(1 - most precise, 4 ñ least precise)

Mouse	Speech3	Gesture	Multimodal

6. Which interface made it hardest for you to remember the symbols?
(1 - hardest, 4 - easiest)

Mouse	Speech3	Gesture	Multimodal

7. Overall, which interface is the most effective?
(1 - most effective, 4 - least effective)

Mouse	Speech3	Gesture	Multimodal

8. Which interface gave you the sensation of being in the map, i.e. you were present and part of the virtual environment.
(1 - most present, 4 - least present)

Mouse	Speech3	Gesture	Multimodal

9. Which interface was the most comfortable to use?
(1 - most comfortable, 4 - least comfortable)

Mouse	Speech3	Gesture	Multimodal

10. Which interface would you most like to have on your own computer?
(1 - most like, 4 - least like)

Mouse	Speech3	Gesture	Multimodal

Figure 44: Multimodal Interface Study: Post-Experiment Questionnaire (Page 1 of 2)

Cognitive Load for Multimodal Speech and Gesture Interfaces
Post-Experiment Questionnaire
Part II

Subject Number:____________

Instructions : Write answers below.

What aspects of the Mouse interface were helpful to you?

What aspects of the Mouse interface were problems for you?

How could the Mouse interface be improved?

What aspects of the Speech interface were helpful to you?

What aspects of the Speech interface were problems for you?

How could the Speech interface be improved?

What aspects of the Gesture interface were helpful to you?

What aspects of the Gesture interface were problems for you?

How could the Gesture interface be improved?

What aspects of the Multimodal interface were helpful to you?

What aspects of the Multimodal interface were problems for you?

How could the Multimodal interface be improved?

Figure 45: Multimodal Interface Study: Post-Experiment Questionnaire (Page 2 of 2)

Subject	Mouse Pause	Mouse Target 1	Mouse Target 2	Mouse Target 3	Mouse Target 4	Speech Pause	Speech Target 1	Speech Target 2	Speech Target 3	Speech Target 4
1	1.216	28.968	20.409	17.145	30.504	1.553	105.99	84.421	72.284	66.006
2	0.531	25.296	37.714	34.941	29.011	1.232	96.098	98.832	88.527	106.65
3a	1.021	24.375	33.238	24.546	32.336	0.691	82.189	112	109.3	97.179
4	0.51	23.694	26.278	19.889	20.99	1.613	101.67	86.775	79.083	90.832
5	0.821	16.785	30.403	24.886	20.129	1.503	107.05	84.952	91.641	95.468
6	0.661	19.558	59.135	28.842	28.971	1.012	95.857	141.37	70.581	105.69
7	1.151	35.461	36.342	56.782	33.428	1.142	136.35	199.64	204.48	150.68
8	0.781	23.213	25.898	31.054	24.215	-0.055	113.43	93.013	185.72	106.42
9	1.141	18.747	22.511	22.674	24.485	0.711	66.215	121.31	83.97	81.558
10	0.711	21.711	22.198	20.063	18.687	0.801	101.57	82.829	89.84	83.56
11	0.5	21.742	21.961	21.501	22.873	0.075	85.493	80.426	64.292	76.55
12	0.791	32.757	39.918	32.496	36.523	0.751	105.31	91.001	91.812	89.829
13	0.711	24.766	20.77	23.333	22.873	0.55	91.462	126.14	130.92	115.55
14	1.793	34.465	32.832	26.648	28.25	1.162	63.451	77.962	50.913	89.98
15	1.232	35.43	21.241	28.831	18.787	1.695	84.721	145.65	128.86	207.01
16	1.22	21.702	35.801	33.839	35.882	1.322	99.613	95.778	114.41	118.56
17	0.902	36.963	39.128	37.252	39.106	1.091	86.404	99.544	79.905	89.628
18	1.442	29.242	26.579	19.408	26.798	1.532	92.163	89.639	126.98	108.48
19	1.192	30.474	53.437	29.252	30.914	1.433	92.893	64.853	82.599	69.851
20	0.871	27.81	21.861	27.991	21.871	1.192	110.95	115.36	107.35	110.94
21	1.973	20.42	25.545	20.04	20.75	1.071	58.254	61.462	59.302	69.96
22	1.264	22.1	37.053	31.325	32.376	1.642	72.374	89.819	90.15	73.296
23	0.52	28.351	29.282	30.604	31.105	0.601	61.208	117.33	70.822	76.099
24	0.831	16.644	19.788	18.197	24.181	0.962	76.66	91.171	76.49	86.214
3	0.831	13.199	25.617	35.301	29.522	1.562	121.49	183.68	174.48	138.2
	Mean	25.861	30.805	27.564	27.294	Mean	91.141	102.14	97.926	98.582
	Stdev	6.0765	10.289	8.4385	5.9274	Stdev	18.712	29.78	36.875	30.139

Subject	Gesture Pause	Gesture Target 1	Gesture Target 2	Gesture Target 3	Gesture Target 4	Multimodal Pause	Multimodal Target 1	Multimodal Target 2	Multimodal Target 3	Multimodal Target 4
1	2.199	96.102	172.46	192.99	302.29	0.802	144.51	120.47	93.103	90.981
2	0.453	150.56	304.47	166.96	174.64	1.242	134.11	79.074	113.78	120.16
3a	0.881	314.33	122.76	143.56	144.51	0.781	94.386	92.723	89.99	91.922
4	1.112	155.48	232.48	188.13	203.22	0.671	138.13	119.22	128.98	97.571
5	0.661	157.37	176.28	225.78	152.16	0.217	104.75	103.28	71.794	92.232
6	0.701	N/A	N/A	N/A	N/A	0.246	273.21	128.54	96.439	114.63
7	0.882	337.7	236.15	283.88	224.83	0.882	131.87	130.25	160.5	128.74
8	0.631	251.98	219.04	N/A	N/A	1.202	93.114	86.504	114.16	95.818
9	0.801	210.11	394.13	N/A	N/A	0.811	110.29	81.647	89.529	84.491
10	1.688	170	171.04	148.3	N/A	0.942	85.983	107.06	82.429	102.25
11	0.811	182.98	187.05	135.67	123.23	0.631	94.846	85.723	113.7	108.18
12	0.641	279.94	269.02	175.11	166.98	0.981	111.54	212.35	94.816	113.3
13	1.072	247.54	191.49	188.48	N/A	0.671	81.007	86.024	71.679	84.766
14	1.742	289.43	N/A	N/A	N/A	1.462	91.071	128.3	87.276	91.752
15	0.802	234.45	343.82	191.6	211.35	1.092	245.29	136.39	153.66	139.53
16	1.752	166.45	256.86	172.45	153.9	1.352	136.03	107.06	154.83	162.43
17	0.651	N/A	N/A	N/A	N/A	1.422	111.67	126.59	97.961	152.81
18	0.832	132.27	239.5	N/A	N/A	1.893	91.081	195.17	120.88	140.22
19	0.426	N/A	N/A	N/A	N/A	2.083	100.69	92.854	95.186	138.71
20	0.912	256.09	224.65	281.04	167.83	0.511	103.98	137.37	163.79	119.37
21	0.811	185.62	172.66	152.33	151.5	0.601	83.41	102.74	100.95	82.559
22	1.012	143.75	302.16	260.23	188.87	1.953	109.65	132.5	159.8	102.57
23	-0.079	109.65	145.05	N/A	N/A	0.731	102.77	107.74	94.277	145.8
24	1.442	225.47	134.13	151.84	150.93	1.252	80.626	89.479	91.191	122.3
3	1.583	N/A	N/A	N/A	N/A	0.093	90.891	179.52	N/A	N/A
	Mean	204.63	224.76	191.15	179.73	Mean	118.92	116.21	110.03	113.46
	Stdev	67.635	71.385	47.677	45.157	Stdev	47.284	32.919	28.844	23.557

All values are times in seconds

Subject 3 omitted from analysis due to time constraints during trial

Figure 46: Multimodal Interface Study: Trial Completion Times

		Mouse 1	Mouse 2	Mouse 3		Speech 1	Speech 2	Speech 3		Gesture 1	Gesture 2	Gesture 3		Multimodal 1	Multimodal 2	Multimodal 3	
Subject	Order	Symbol	Order	Position	Total	Symbol	Order	Position	Total	Symbol	Order	Position	Total	Symbol	Order	Position	Total
1	M S G U	3	4	3	10	4	4	4	12	4	4	2	10	4	4	4	12
2	M S U G	4	4	2	10	4	4	4	12	4	4	4	12	4	4	4	12
3a	M G S U	4	4	4	12	2	3	3	8	2	3	4	9	0	0	1	1
4	M G U S	4	4	2	10	4	4	2	10	4	4	4	12	4	4	0	8
5	M U S G	0	0	4	4	3	4	4	11	4	4	4	12	3	1	0	4
6	M U G S	4	4	3	11	4	4	3	11				0	3	4	2	9
7	S M G U	3	2	2	7	4	3	1	8	2	2	1	5	1	1	3	5
8	S M U G	4	4	4	12	3	4	4	11	2	2	2	6	4	4	3	11
9	S G M U	3	4	4	11	1	1	1	3	2	2	2	6	2	3	3	8
10	S G U M	4	4	4	12	3	4	4	11	2	3	3	8	4	4	2	10
11	S U M G	4	4	3	11	4	3	3	10	4	4	4	12	2	3	2	7
12	S U G M	4	4	3	11	4	4	4	12	3	4	1	8	3	2	1	6
13	G M S U	4	4	4	12	4	4	4	12	3	4	2	9	4	4	4	12
14	G M U S	4	4	4	12	4	4	4	12	1	1	1	3	2	1	3	6
15	G S M U	4	3	4	11	3	4	2	9	4	4	4	12	2	3	2	7
16	G S U M	3	2	4	9	4	4	2	10	4	4	4	12	4	4	0	8
17	G U M S	4	4	4	12	4	3	4	11				0	3	4	3	10
18	G U S M	2	1	3	6	3	3	2	8	2	2	3	7	3	2	2	7
19	U M S G	4	4	3	11	3	4	2	9				0	4	4	1	9
20	U M G S	4	4	3	11	4	4	3	11	4	4	4	12	4	3	2	9
21	U S M G	4	4	4	12	4	4	3	11	4	4	4	12	4	4	4	12
22	U S G M	4	4	4	12	4	4	4	12	4	4	3	11	4	3	4	11
23	U G M S	3	2	3	8	4	4	4	12	2	2	2	6	4	4	3	11
24	U G S M	3	4	2	9	4	4	4	12	4	4	4	12	4	4	3	11
3	M G S U	3	2	2	7	2	3	3	8				0	1	0	2	3
Average		3.50	3.42	3.33	10.25	3.54	3.67	3.13	10.33	3.10	3.29	2.95	9.33	3.17	3.08	2.33	8.58
Std Dev		0.93	1.14	0.76	2.13	0.78	0.70	1.03	2.08	1.04	1.01	1.16	2.90	1.13	1.25	1.31	2.86

Summary		M	S	G	U
symbols	Average	3.50	3.54	3.10	3.17
	Std Dev.	0.93	0.78	1.04	1.13
order	Average	3.42	3.67	3.29	3.08
	Std Dev.	1.14	0.70	1.01	1.25
position	Average	3.33	3.13	2.95	2.33
	Std Dev.	0.76	1.03	1.16	1.31
total	Average	10.25	10.33	9.33	8.58
	Std Dev.	2.13	2.08	2.90	2.86

Subject 3 Excluded

Units are number of landmarks correctly identified, ordered, or placed

Figure 47: Multimodal Interface Study: Memory Task Results

Question:	1. Learn				2. Use				3. Errors				4. Fast				5. Precise			
Interface:	M	S	G	U	M	S	G	U	M	S	G	U	M	S	G	U	M	S	G	U
Subject																				
1	2	1	5	2	4	4	5	4	3	3	1	2	4	4	5	4	2	5	5	4
2	1	2	5	4	1	2	3	5	5	3	3	2	3	3	3	4	2	2	2	4
3a	1	1	3	2	2	2	4	2	4	4	2	3	2	3	3	2	1	2	4	3
4	1	4	5	4	1	4	5	4	3	3	1	3	2	3	5	4	3	4	5	4
5	1	2	2	2	1	2	3	3	3	4	3	3	2	2	4	2	2	3	4	2
6	1	2	2	2	2	2	4	3	4	4	2	3	2	3	4	4	2	3	4	3
7	1	2	5	4	1	2	5	4	4	3	1	2	1	4	5	3	1	4	5	4
8	1	1	2	4	1	1	4	4	5	4	2	2	1	4	4	4	1	4	2	2
9	1	1	4	3	1	2	5	3	5	4	2	2	1	3	5	4	1	3	5	4
10	1	1	3	3	1	1	4	3	4	4	2	3	1	3	5	4	2	3	5	4
11	1	2	2	2	1	4	3	4	5	4	3	2	1	5	4	2	1	3	2	2
12	1	1	1	4	1	3	5	5	4	4	1	2	1	3	5	4	1	4	4	3
13	1	1	2	1	1	1	3	1	4	4	3	3	1	1	4	2	1	3	5	3
14	1	1	5	2	1	2	5	3	5	3	2	3	1	2	5	4	1	3	4	3
15	1	1	2	2	1	2	4	4	5	4	2	2	1	2	5	4	1	2	5	3
16	1	1	3	4	1	1	4	4	4	4	3	4	1	2	4	4	1	3	4	4
17	1	1	2	2	1	2	4	3	4	4	3	3	1	2	2	2	1	3	4	4
18	1	1	2	1	1	1	4	2	5	4	4	2	1	2	5	2	1	1	4	3
19	2	2	4	2	2	2	4	2	2	3	1	4	2	2	4	3	2	2	4	2
20	1	1	2	2	1	1	2	2	5	3	2	3	1	1	5	1	1	2	4	2
21	1	2	4	2	1	2	5	3	3	4	2	3	1	2	5	4	1	3	5	3
22	1	1	1	1	1	1	2	1	4	3	3	3	1	3	3	3	1	3	3	2
23	1	2	2	2	1	2	4	2	4	4	2	4	1	2	4	2	1	2	4	3
24	1	2	2	2	1	2	3	4	4	4	2	4	1	2	3	4	1	2	3	3
3	1	1	2	2	3	1	5	3	3	4	2	3	2	2	5	2	3	2	5	2
Average:	1.92	1.50	0.08	0.54	1.75	1.00	-0.92	-0.13	-1.08	-0.67	0.83	0.21	1.58	0.38	-1.21	-0.17	1.67	0.13	-1.00	-0.08
Stddev:	0.28	0.72	1.35	1.02	0.68	0.93	0.93	1.12	0.83	0.48	0.82	0.72	0.78	0.97	0.88	1.01	0.56	0.90	0.98	0.78

Question:	6. Remember				7. Effective				8. Presence				9. Comfort				10. Want			
Interface:	M	S	G	U	M	S	G	U	M	S	G	U	M	S	G	U	M	S	G	U
Subject																				
1	3	3	2	3	2	2	4	2	2	2	5	4	4	3	5	4	4	3	5	4
2	2	2	1	4	2	2	3	5	3	2	4	2	2	2	2	4	2	2	3	5
3a	4	4	4	5	2	2	4	2	3	3	2	1	2	2	3	3	2	2	3	2
4	3	3	4	3	2	4	5	4	3	4	5	4	2	4	5	4	3	4	5	4
5	2	3	2	4	2	2	3	2	2	2	2	2	1	2	3	3	2	2	4	2
6	2	3	3	4	2	2	4	3	4	4	2	2	2	3	4	4	2	2	3	3
7	4	2	5	4	2	3	4	3	3	2	3	2	1	2	5	4	1	2	5	4
8	2	2	2	4	1	3	4	4	4	2	3	4	2	2	4	4	2	3	4	4
9	1	4	3	3	1	2	4	3	2	2	4	4	1	2	5	3	1	3	5	4
10	2	2	5	4	2	2	4	3	3	3	4	4	1	2	4	4	1	3	4	3
11	1	4	2	4	1	4	2	3	2	4	3	3	2	3	3	4	1	3	3	3
12	1	4	5	5	1	3	5	4	5	4	5	4	1	4	5	5	5	4	5	5
13	1	4	2	4	1	2	4	2	4	4	4	4	1	2	4	4	1	3	4	3
14	2	2	3	5	1	2	5	3	3	3	5	4	2	2	4	4	2	2	5	4
15	3	4	5	5	1	3	5	5	1	4	5	5	1	3	5	5	1	3	5	5
16	4	3	1	5	1	1	3	3	1	2	4	5	1	2	2	3	1	1	4	3
17	1	4	2	2	1	2	4	2	2	2	2	3	1	2	2	2	1	3	3	3
18	3	4	2	5	1	1	4	2	5	2	1	1	3	2	3	2	2	2	5	4
19	4	4		3	2	2	5	2	4	2	4	1	2	2	4	2	2	2	5	2
20	4	4	1	3	1	1	3	2	5	3	5	1	1	2	3	4	1	2	4	2
21	2	5	1	3	1	2	5	4	4	3	4	3	1	3	5	4	2	4	5	5
22	1	3	3	4	1	1	3	2	2	1	1	1	1	1	2	1	1	1	2	1
23	4	3	3	3	1	2	4	2	1	2	3	2	1	2	4	3	1	2	5	4
24	2	2	2	3	1	2	3	3	1	2	2	2	1	2	4	4	1	2	4	4
3	3	2		2	2	2	4	3	5	2	2	2	2	2	4	3	2	2	4	3
Average:	0.58	-0.25	0.26	-0.83	1.63	0.83	-0.92	0.08	0.13	0.33	-0.42	0.17	1.46	0.67	-0.75	-0.50	1.25	0.50	-1.17	-0.46
Stddev:	1.14	0.90	1.36	0.87	0.49	0.82	0.83	0.97	1.30	0.92	1.32	1.34	0.78	0.70	1.07	0.98	1.03	0.83	0.92	1.10

Question Responses: 1 strongly agree, 2, agree, 3 indifferent, 4 disagree, 5 strongly disagree

Subject 3 excluded

Figure 48: Multimodal Interface Study: Post-Trial Interface Ratings

Question:	1. Learn				2. Use				3. Errors				4. Fastest				5. Precise			
Rankings:	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Subject																				
1	S	M	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	U	S	G
2	M	S	U	G	M	S	G	U	U	G	S	M	M	S	G	U	M	S	G	U
3a	M	U	S	G	M	U	S	G	G	U	S	M	M	U	S	G	M	S	U	G
4	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
5	M	S	U	G	M	S	G	U	G	U	S	M	M	S	U	G	M	S	U	G
6	M				M				G				M				M			
7	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
8	M	S	G	U	U	G	S	M	G	U	S	M	M	S	U	G	M	S	U	G
9	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
10	M	S	U	G	M	U	S	G	G	U	S	M	M	U	S	G	M	U	S	G
11	M	S	U	G	M	G	S	U	U	S	G	M	M	S	U	G	M	G	U	S
12	M	S	G	U	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
13	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
14	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
15	M	S	G	U	M	S	G	U	U	G	S	M	M	S	U	G	M	S	U	G
16	M	S	G	U	M	S	G	U	G	S	U	M	M	S	G	U	M	S	G	U
17	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
18	M	S	U	G	M	S	U	G	G	U	S	M	M	U	S	G	M	S	U	G
19	S	M	U	G	S	M	U	G	G	U	M	S	M	S	U	G	S	M	U	G
20	M	S	G	U	M	S	G	U	G	U	S	M	M	S	G	U	M	S	G	U
21	M	S	U	G	M	S	U	G	G	S	U	M	M	S	U	G	M	S	U	G
22	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	S	U	G
23	M	S	U	G	M	U	S	G	G	S	U	M	M	U	S	G	M	U	S	G
24	M	S	U	G	M	S	U	G	G	U	S	M	M	S	U	G	M	U	S	G
3	M	S	U	G	M	S	U	G	G	S	U	M	M	S	U	G	M	S	U	G
Responses per rank																				
Mouse (M)	23	2	0	0	23	1	0	1	0	0	1	23	25	0	0	0	24	1	0	0
Speech (S)	2	21	1	0	1	18	5	0	0	5	18	1	0	20	4	0	1	18	4	1
Gesture (G)	0	0	5	19	0	2	5	17	22	2	1	0	0	0	3	21	0	1	3	20
Multimodal (U)	0	1	18	5	1	3	14	6	3	17	4	0	0	4	17	3	0	4	17	3
Total	25	24	24	24	25	24	24	24	25	24	24	24	25	24	24	24	25	24	24	24

Question:	6. Remember				7. Effective				8. Presence				9. Comfort				10. Want			
Rankings:	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Subject																				
1	U	G	S	M	M	S	U	G	S	M	U	G	M	S	U	G	M	S	U	G
2	U	S	M	G	M	S	G	U	U	S	M	G	M	S	G	U	M	S	G	U
3a	U	S	G	M	M	U	S	G	U	G	S	M	M	S	U	G	M	S	U	G
4	S	G	U	M	M	S	U	G	M	S	U	G	M	S	U	G	M	S	U	G
5	U	S	G	M	M	S	U	G	U	M	S	G	M	S	U	G	M	S	U	G
6	G				M				U				M				M			
7	G	U	S	M	M	S	U	G	U	S	G	M	M	S	U	G	U	M	S	G
8	U	G	S	M	M	S	G	U	S	G	U	M	M	S	G	U	M	S	G	U
9	G	U	S	M	M	S	U	G	S	U	M	G	M	S	U	G	M	S	U	G
10	U	G	S	M	M	U	S	G	U	M	S	G	M	S	U	G	M	S	U	G
11	U	S	G	M	M	G	S	U	M	S	G	U	M	S	G	U	M	G	S	U
12	U	G	S	M	M	S	U	G	U	G	S	M	M	S	U	G	M	U	S	G
13	U	S	G	M	M	S	U	G	M	G	S	U	M	S	G	U	M	S	U	G
14	G	U	S	M	M	S	U	G	S	M	U	G	M	S	U	G	M	S	U	G
15	U	S	M	G	M	S	U	G	M	S	U	G	M	S	G	U	M	S	G	U
16	U	M	G	S	M	S	G	U	M	S	G	U	M	S	G	U	S	G	U	M
17	S	U	G	M	M	S	U	G	U	G	S	M	M	S	U	G	M	S	U	G
18	S	M	U	G	M	S	U	G	U	S	G	M	M	S	U	G	M	S	U	G
19	G	M	S	U	S	M	U	G	S	U	M	G	S	M	U	G	S	M	U	G
20	S	M	U	G	M	S	G	U	U	G	M	S	M	S	G	U	G	S	U	M
21	M	S	U	G	M	S	U	G	U	S	M	G	M	S	U	G	M	S	U	G
22	U	G	S	M	M	S	U	G	U	S	G	M	M	S	U	G	M	S	U	G
23	M	U	S	G	M	S	U	G	M	S	U	G	M	S	U	G	M	S	U	G
24	U	G	S	M	M	S	U	G	U	S	M	G	M	S	U	G	M	S	U	G
3	M	U	S	G	M	S	U	G	U	G	S	M	M	S	U	G	M	S	U	G
Responses per rank																				
Mouse (M)	3	4	2	15	24	1	0	0	6	4	6	8	24	1	0	0	21	2	0	2
Speech (S)	4	7	12	1	1	20	3	0	5	11	7	1	1	23	0	0	2	19	3	0
Gesture (G)	5	7	6	7	0	1	4	19	0	7	5	12	0	0	7	17	1	2	3	18
Multimodal (U)	13	6	4	1	0	2	17	5	14	2	6	3	0	0	17	7	1	1	18	4
Total	25	24	24	24	25	24	24	24	25	24	24	24	25	24	24	24	25	24	24	24

Subject 3 excluded

Figure 49: Multimodal Interface Study: Post-Experiment Interface Rankings

APPENDIX B

ISOMETRIC JOYSTICK INTERFACE STUDY

The following pages contain copies of materials used during the isometric joystick study. Some of these materials may be reproduced at smaller than original scale to satisfy dissertation formatting.

Abbreviations in these materials for the different interface types include:

B : Bulldozer, a two handed interface using a bulldozer metaphor.

A : Airplane, a two handed interface using an aircraft metaphor.

TB : Bulldozer with Tilt, a two handed interface using a bulldozer metaphor.

TA : Airplane with Tilt, a one handed interface using an aircraft metaphor.

Title	Number of Pages
Consent Form	1
Isometric Joystick Study: Pre-Experiment Questionnaire	1
Isometric Joystick Study: Symbol Familiarity Exercise	1
Isometric Joystick Study: Exocentric Landmark Test	1
Isometric Joystick Study: Egocentric Landmark Test	1
Isometric Joystick Study: Mid-Experiment Questionnaire	1
Isometric Joystick Study: Post-Experiment Questionnaire	2
Isometric Joystick Study: Trial Completion Times	1
Isometric Joystick Study: Exocentric Memory Task Results	1
Isometric Joystick Study: Egocentric Memory Task Results	1
Isometric Joystick Study: Post-Trial Interface Ratings	1
Isometric Joystick Study: Post-Experiment Interface Rankings	1

Table 11: List of Appended Materials from the Isometric Joystick Study

Comparison of Interfaces for Mobile and Wearable 3D Visualization
Informed Consent Form

Title of Research Study

The title of this study is "Comparison of Interfaces for Mobile and Wearable 3D Visualization."

Investigators

David M Krum	Bill Ribarsky
Principal Investigator	Faculty Sponsor
dkrum@cc.gatech.edu	ribarsky@cc.gatech.edu

College of Computing, Georgia Institute of Technology

Purpose of Research

You are being asked to volunteer for a research study to examine different computer interfaces. These interfaces use IBM Trackpoint pointing devices in a variety of manners. The different interfaces are being tested to determine speed, accuracy, and how much mental effort they require. Eligible participants are 18 years or older..

Procedures Used in the Study

Your participation should last approximately one hour. You will first be asked to perform a short-term memory test and a spatial abilities test. You will then fill out a questionnaire to allow us to evaluate how much experience you have had with computers interfaces.

You will be navigating a 3D terrain visualization. You will use four different styles of computer interfaces, each using IBM Trackpoint pointing devices.

You will see various icons while using each interface. After using each interface, you will be given a test to see if you can remember which icons you saw. You will also be given a questionnaire that will ask questions about your experience with the user interface.

After you use all four interfaces, you will be given a final questionnaire about your experience.

Foreseeable Risks from the Study

Only minimal risks are expected. These risks should be no greater than those expected from typical computer use.

Potential Benefits from the Study

There is no direct benefit to you by participating, however we hope that your participation in this study will lead to better computer interfaces for mobile and wearable computers. You may also gain a greater understanding of computer interface technology.

Compensation/Costs

You will receive 1 hour of extra credit for you participation in this study. The effect of that extra credit on your course grade is a decision to be made by the instructor. You will receive no financial compensation for your participation.

Alternative Procedures

Alternative opportunities to receive extra credit are available should you choose not to participate in this experiment. These include reading and reviewing a paper on computer interface technology or writing a report about a particular computer interface technology.

Confidentiality of Records

All information about you, including the questionnaires, computer files, and assessment results will be kept private. Your results will be confidential and will be reported anonymously in any article that this research may generate. All data will be coded and kept in a secured, limited access location. . Your identity will not be revealed in any publication or presentation of the results of this research. However, confidentiality cannot be guaranteed; your personal information may be disclosed if required by law.

Disclosure Statement

The researchers have no financial interests in the results of the study. However, they may publish the results of the study.

Injury/Adverse Reactions

Any injuries or reactions should be reported to David Krum at (404) 894-6710 or Dr. Bill Ribarsky at (404) 894-6148. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.

Contact Persons

To make inquiries regarding this study, contact David Krum at (404) 385-0256. His office is Centennial Research Building 375. You may also contact Dr. Bill Ribarsky at (404) 894-6148. His office is Centennial Research Building 371.

Voluntary Participation/Withdrawal

Participation in this study is voluntary. You are free to withdraw from participation at any time. Refusal to participate will involve no penalty or loss of benefits to which the subject is otherwise entitled. Under certain circumstances, participants may be withdrawn from the study without their consent if the researcher decides that it is not in their best interest, or if they fail to follow the procedures. If you wish to withdraw from participation, please tell the researcher at any time.

You have rights as a research volunteer. Taking part in this study is completely voluntary. If you do not take part, you will have no penalty. You may stop taking part in this study at any time with no penalty. If you have any questions about the informed consent document, or the consent process, or your rights as a research volunteer, contact:

Office of Research Compliance
Georgia Institute of Technology
Atlanta, Georgia 30332-0420
Voice (404) 894-6944
Fax (404) 385-0864
irb@gatech.edu

A copy of this form will be given to you.

Your signature below indicates that the researchers have answered all of your questions to your satisfaction and that you consent to volunteer for this study.

______________________________ ________________
Signature of Participant Date

____
Name of Participant (Please Print)

______________________________ ________________
Signature of Investigator Date

Figure 50: Isometric Joystick Study: Consent Form

Comparison of Interfaces for Mobile and Wearable 3D Visualization
Pre-Experiment Questionnaire

Subject Number:

Gender: (circle one)	Age in years: (fill in)
Male Female	_______________

Circle one:

	Never	Seldom	Sometimes	Frequently
Do you a computer for work? (Word processing, spreadsheets, design, etc.)	1	2	3	4
Do you use a computer for entertainment? (Games, chat, etc.)	1	2	3	4
Do you play first person 3D computer games such as Quake, Unreal, etc?	1	2	3	4
Do you play real time strategy games such as Civilization, Warcraft, Tiberian Sun, etc?	1	2	3	4
Do you use 3D design software like Autocad or 3D Studio Max?	1	2	3	4

Circle one:

What is your preferred pointing device for gaming?	Mouse, Trackpoint, Trackpad, Trackball, Stylus, Joystick, Steering Wheel, other __________________
What is your preferred pointing device for computer work?	Mouse, Trackpoint, Trackpad, Trackball, Stylus, other __________________

Figure 51: Isometric Joystick Study: Pre-Experiment Questionnaire

Comparison of Interfaces for Mobile and Wearable 3D Visualization
Pre-Experiment Symbols

Subject:

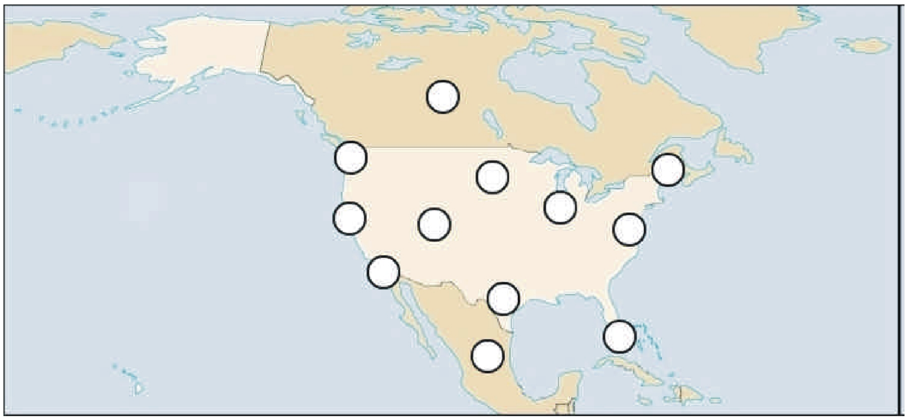
Instructions: Come up with a one-word name for each symbol. Write the name below each symbol.

Figure 52: Isometric Joystick Study: Symbol Familiarity Exercise

Comparison of Interfaces for Mobile and Wearable 3D Visualization
Mid-Experiment Test

<table>
<tr><td rowspan="3">Subject:</td><td rowspan="3">Trial:</td><td colspan="3">Type:</td></tr>
<tr><td>Bulldozer</td><td>Airplane</td><td>Mouse</td></tr>
<tr><td>Tilt Bulldozer</td><td>Tilt Airplane</td><td></td></tr>
</table>

1. Find numbers for the symbols you saw. Write the numbers on the map below in the appropriate locations.



2. What order did you see the symbols? Write the numbers below. Put the first symbol you saw first.

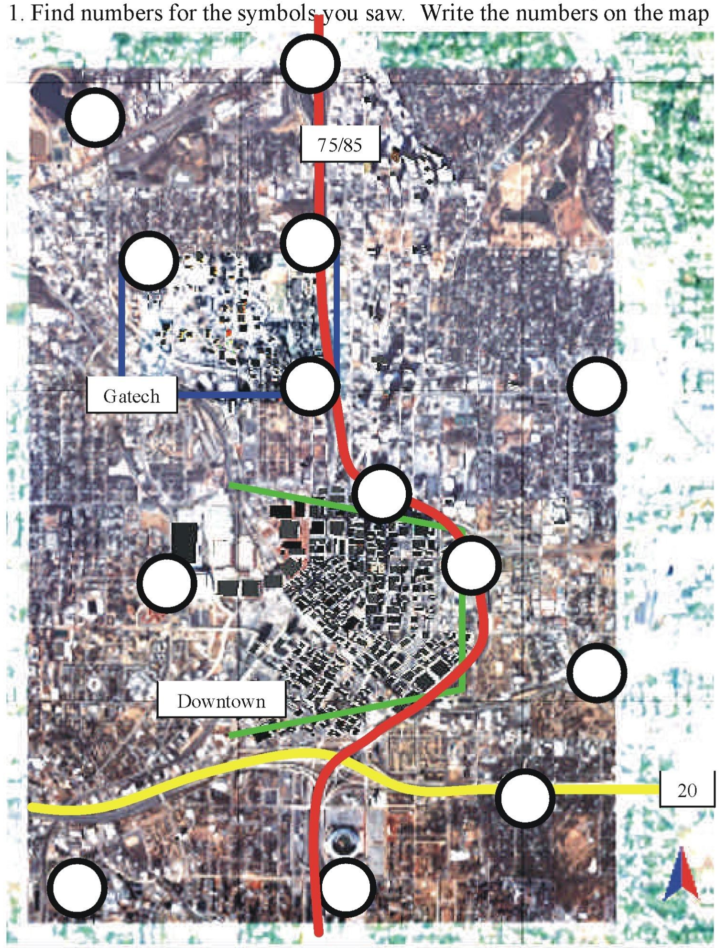
First Second Third Fourth

Figure 53: Isometric Joystick Study: Exocentric Landmark Test

Comparison of Interfaces for Mobile and Wearable 3D Visualization Mid-Experiment Test

Subject:	Trial:		Bulldozer	Airplane	Mouse
			Tilt Bulldozer	Tilt Airplane	

1. Find numbers for the symbols you saw. Write the numbers on the map



2. What order did you see the symbols? Write the numbers below. Put the first symbol you saw first.

First Second Third Fourth

Figure 54: Isometric Joystick Study: Egocentric Landmark Test

Comparison of Interfaces for Mobile and Wearable 3D Visualization
Mid-Experiment Questionnaire

Subject:	Trial:	Type:		
		Bulldozer	Airplane	Mouse
		Tilt Bulldozer	Tilt Airplane	

Instructions : Read the statements and circle your answers.

1. This interface is easy to learn.

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

2. This interface is easy to use.

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

3. This interface has a lot of errors.

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

4. This interface allows fast navigation?

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

5. This interface allows precise navigation?

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

6. It is easy to remember the symbols while using this interface.

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

7. This interface is comfortable to use.

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

8. Overall, this is an effective interface.

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

9. I would like to have this interface on my own computer?

Strongly Disagree	Disagree	Indifferent	Agree	Strongly Agree
1	2	3	4	5

10. What aspects of this interface were helpful to you? (Write in your answer)

11. What aspects of this interface were problems for you? (Write in your answer)

Figure 55: Isometric Joystick Study: Mid-Experiment Questionnaire

Cognitive Load for Multimodal Speech and Gesture Interfaces

Post-Experiment Questionnaire

Part I

Subject Number:

Instructions : *Rank* the interfaces in order. *Write the number* in the boxes below.

1. Which interface is easiest to learn? (1 - easiest, 4 - hardest)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

2. Which interface is easiest to use? (1 - easiest, 4 - hardest)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

3. Which interface had the most errors? Which interface didnít do what you wanted? (1 - most errors, 4 ñleast errors)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

4. Which interface allows the fastest navigation? (1 - fastest, 4 - slowest)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

5. Which interface allows the most precise navigation? (1 - most precise, 4 ñ least precise)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

6. Which interface made it hardest for you to remember the symbols? (1 - hardest, 4 - easiest)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

7. Which interface was the most comfortable to use? (1 - most comfortable, 4 - least comfortable)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

8. Overall, which interface is the most effective? (1 - most effective, 4 - least effective)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

9. Which interface would you most like to have on your own computer? (1 - most like, 4 - least like)

Bulldozer	*Airplane*	*Bulldozer with Tilt*	*Airplane with Tilt*

Figure 56: Isometric Joystick Study: Post-Experiment Questionnaire (Page 1 of 2)

Cognitive Load for Multimodal Speech and Gesture Interfaces
Post-Experiment Questionnaire
Part II

Subject Number:

Instructions : Write answers below.

What aspects of the *Bulldozer* interface were helpful to you?

What aspects of the *Bulldozer* interface were problems for you?

How could the *Bulldozer* interface be improved?

What aspects of the *Airplane* interface were helpful to you?

What aspects of the *Airplane* interface were problems for you?

How could the *Airplane* interface be improved?

What aspects of the *Bulldozer with Tilt* interface were helpful to you?

What aspects of the *Bulldozer with Tilt* interface were problems for you?

How could the *Bulldozer with Tilt* interface be improved?

What aspects of the *Airplane with Tilt* interface were helpful to you?

What aspects of the *Airplane with Tilt* interface were problems for you?

How could the *Airplane with Tilt* interface be improved?

Figure 57: Isometric Joystick Study: Post-Experiment Questionnaire (Page 2 of 2)

Subject/Trial	5	6	3	4	1	2	7	8
1	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	43.703	33.234	30.5	26.578	39.561	15.672	47.593	29.453
	56.891	51.235	43	17.314	54.672	13.031	71.938	25.516
	62.562	26.359	60.282	16.123	38.921	47.062	63.656	6.484
	58.641	43.437	29.109	10.078	41.657	18.203	68.016	18
Subject/Trial	5	6	3	4	7	8	1	2
2	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	46.375	28.687	44.172	23.437	46.203	38.078	55.295	45.609
	48.451	29.016	43.25	23.11	48.516	18.719	76.015	40.562
	56.31	15.313	51.969	25.859	47.531	24.984	66.516	45.746
	69.083	30.75	43.062	21.469	44.719	20.313	77.453	32.692
Subject/Trial	5	6	7	8	1	2	3	4
3	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	31.063	16.687	34.375	13.61	91.671	30.187	96.546	16.141
	42.218	23.625	42.594	61.25	46.032	36.203	56.5	25.828
	265.246	30.656	46.578	97.875	53.328	50.375	44.579	20.359
	43.192	30.328	56.266	22.094	58.64	48.485	48.302	10.5
Subject/Trial	5	6	1	2	7	8	3	4
4	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	48.641	43.953	53.656	15.766	51.234	29.203	65.735	26.781
	69.718	47.047	60.141	37.047	69.219	31.484	65.875	21.984
	117.797	68.109	56.625	80.771	63.047	11.875	63.499	15.625
	66.485	39.813	59.282	50.494	55.968	32.078	60.548	16.094
Subject/Trial	5	6	7	8	3	4	1	2
5	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	54.312	38.218	34.891	39.422	70.453	32.125	116.671	107.657
	75.266	59.936	87.406	33.437	83.5	41.86	109.969	57.267
	72.234	89.861	62.734	27.766	83.047	30.25	201.797	49.779
	64.031	73.578	63.094	42.406	76.484	120.265	188.313	47.172
Subject/Trial	5	6	1	2	3	4	7	8
6a	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	50.547	33.047	46.843	17.437	56.14	32.469	44.69	57.906
	81.875	35.938	73.735	45.422	62.813	29.156	58.032	22.719
	97.75	22.92	76.172	53.437	61.75	28.502	46.498	33.281
	90.299	34.064	82.859	66.094	66.828	44.15	60.345	14.313
Subject/Trial	3	4	5	6	1	2	7	8
7	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	44.047	19.422	59.889	51.969	83.062	32.52	65.359	63.844
	67.266	40.719	86.421	53.469	114.781	66.386	58	28.067
	51.234	42.406	93.69	50.844	60.578	47.235	50.078	6.652
	53.188	23.484	67.69	30.015	56.938	43.281	70.829	15.781
Subject/Trial	3	4	5	6	7	8	1	2
8	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	160.669	34.015	45.687	37.015	48.827	34.913	103.811	81.717
	62.358	53.593	72.764	46.311	55.676	30.047	135.685	47.14
	75.733	40.718	64.296	30.64	53.68	33.53	86.42	47.343
	61.827	196.981	100.17	34.99	59.079	172.356	90.858	54.811
Subject/Trial	7	8	5	6	1	2	3	4
9	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	31.296	26.222	21.312	20.688	57.921	25.998	41.046	15.015
	61.718	19.768	41.187	32.311	57.062	34.718	47.515	25.734
	53.921	13.731	41.624	14.957	62.326	26.359	52.291	19.344
	78.514	15.579	38.749	42.339	43.734	26.281	39.535	10.171
Subject/Trial	1	2	5	6	7	8	3	4
10	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	68.233	30.312	32.427	37.234	65.155	39.828	60.592	29.062
	91.045	51.436	57.718	29.937	67.201	61.233	75.108	52.921
	86.045	118.67	74.264	29.952	57.89	40.327	87.545	5.734
	105.498	76.124	69.686	37.031	79.03	32.843	83.593	80.639
Subject/Trial	7	8	5	6	3	4	1	2
11	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	40.742	21.472	36.343	14.781	78.92	30.312	114.951	44.46
	57.694	24.988	60.503	29.484	64.156	14.312	88.67	21.475
	49.171	8.355	37.948	16.843	60.498	21.266	134.513	22.484
	57.53	50.108	44.952	30.515	74.936	13.437	63.077	38.234
Subject/Trial	1	2	5	6	3	4	7	8
12	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	39.655	13.999	32.656	30.046	57.265	13.437	55.03	35.169
	49.156	14.578	40.499	29.937	52.061	17.156	61.437	25.783
	41.015	25.515	36.968	16.468	57.03	12.844	50.171	13.187
	39.108	19.219	35.218	47.265	57.624	9.187	52.124	22.359
Subject/Trial	3	4	7	8	1	2	5	6
13	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	92.452	38.983	44.518	25.737	75.999	28.374	175.902	67.31
	115.716	20.609	52.402	105.514	102.248	44.405	192.2	56.04
	93.405	94.03	39.233	40.202	107.154	76.061	145.56	30.661
	99.751	20.39	55.984	32.984	75.139	48.031	86.123	21.656
Subject/Trial	3	4	1	2	7	8	5	6
14	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	79.859	34.406	87.578	32.406	53.293	43.725	60.734	62.484
	74	43.531	90.641	20.5	78.687	36.634	80.5	91.485
	78.86	14.813	56.625	40.813	77.36	53.672	69.074	10.094
	71.988	107.719	64.422	67.593	89.51	48.781	98.832	32.609

Subject/Trial	7	8	3	4	1	2	5	6
15	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	66.579	41.344	59.013	23.984	86.932	49.125	41.11	33.531
	66.546	39.734	65.3	39.234	83.302	31.343	69.578	57.297
	44.735	10.484	65	151.645	135.985	47.391	82.73	12.328
	71.14	25.594	73.672	32.996	75.593	39.422	81.379	12.828
Subject/Trial	1	2	3	4	7	8	5	6
16	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	36.5	26.344	42.657	10.531	46.031	18.812	42.593	30.832
	85.953	36.838	53.5	26.906	57.375	33.735	60.74	39.735
	55.563	53.427	50.453	53.328	46.172	14.343	77.573	29.937
	56.765	33.938	52.422	49.266	55.922	24.157	55	22.047
Subject/Trial	7	8	1	2	3	4	5	6
17a	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	41.984	23.125	44.172	31.953	55.11	24.379	38.969	20.406
	65.282	109.265	64.172	24.25	81.656	21.188	53.746	31
	63.718	11.703	56.234	30.093	69.75	6.203	69.145	35.313
	75.016	16.985	62.5	160.079	70.578	155.578	67.175	20.406
Subject/Trial	1	2	7	8	3	4	5	6
18	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	116.031	33.797	34.953	46.477	49.898	31.125	66.546	43.13
	142.844	26.563	58.344	29.39	80.235	27.953	71.344	27.713
	85.031	48.406	50.656	39.5	80.219	35.593	77.038	28.032
	72.953	139.234	57.927	35.36	74.808	32	79.978	22.593
Subject/Trial	3	4	7	8	5	6	1	2
19a	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	47.531	15.422	43.313	24.203	54.281	27.91	56.498	19.69
	58.234	21.453	44.562	22.032	61.485	49.813	63.765	26.935
	44.704	37.109	51.125	12.328	75.672	31.747	57.063	45.297
	59.062	27.188	47.891	29.797	74.562	24.815	57.344	39.344
Subject/Trial	3	4	1	2	5	6	7	8
20	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	70.015	24.578	129.363	16.156	42.078	18.01	31.737	23.246
	59.172	28.812	49.25	112.813	51.39	50.203	53.078	19.047
	50.25	10.188	35.641	29.992	61.204	34.317	42.25	19.177
	65.215	77	41.422	32.039	55.515	30.683	51.703	27.26
Subject/Trial	7	8	3	4	5	6	1	2
21	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	39.359	27.281	30.621	9.547	44.25	27.668	43.5	15.969
	46.094	33.781	38.848	18.328	46.969	31.207	57.844	43.312
	65.277	28.938	42.875	16.875	66.6	9.156	55	20.219
	57.582	18.328	31.75	29.484	51.853	21.167	56.672	31.031
Subject/Trial	1	2	3	4	5	6	7	8
22	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	66.605	22.875	47	16.437	64.156	23.047	45.203	24.25
	63.317	26.625	46.328	27.188	54.688	22.313	53.282	18.672
	67.718	36.125	48.656	19.484	66.672	16.234	49.406	21.906
	66.219	40.657	59.36	18.735	65.422	55.016	51.219	54.312
Subject/Trial	1	2	7	8	5	6	3	4
23	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	50.25	55.578	35.422	30.58	38.829	25.14	47.267	24.578
	91.282	67.938	45.047	32.029	55.234	27.969	69.516	35.969
	107.765	57.828	53.328	7.188	61.375	24.719	86.625	103.859
	127.688	72.641	46.719	110.968	75.219	79.969	74.062	78.797
Subject/Trial	7	8	1	2	5	6	3	4
24	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	60.469	51.672	53.375	26.953	47.828	57.207	47.953	48.734
	59.375	61	69.609	31.625	71.672	37.934	55.686	57.638
	62.953	87.172	43.235	34.188	69.359	45.844	48.267	3.081
	60.859	35.281	48.218	32.672	59.844	66.359	51.733	41.859
Subject/Trial	3	4	7	8	5	6	1	2
19	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	45.453	16.703	43.313	16.219	40.171	28.141	44.57	19.454
	54.266	24.622	39.609	14.531	54.75	31.297	56.102	18.796
	56.5	31.378	42.531	13.094	57.625	16.109	44.687	17.11
	92.297	16.14	34.829	16.421	57.787	21.375	48.656	24.812
Subject/Trial	7	8	1	2	3	4	5	6
17	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	50.152	21.5	43.094	18.125	54.958	19.046	38.907	51.672
	73.426	17	87.703	16.438	63.854	30.719	53.428	41.109
	50.359	13.891	39.109	26.312	61.484	22.235	53.16	46.156
	51.11	18.5	43.235	33.656	83.882	37.453	49.208	38.157
Subject/Trial	5	6	1	2	3	4	7	8
6	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
	51.656	29.782	40.563	33.359	63.704	22.313	40.75	23.375
	66.172	28.468	78.156	29.516	70.781	25.047	50.359	14.438
	56.844	21.032	75.23	26.468	76.076	22.047	42.25	7.968
	50.328	17.046	60.129	27.969	64.143	60.156	45.797	21.485

For all subjects except 6, 17, and 19 which were excluded from analysis)

	Orbit B	Fly	Orbit A	Fly	Orbit TB	Fly	Orbit TA	Fly
average	68.35	39.71	52.86	34.49	63.76	35.16	70.49	33.71
stdev	30.88	29.06	17.91	23.48	16.89	22.18	33.37	21.13

Figure 58: Isometric Joystick Study: Trial Completion Times

Orbit	Bulldozer				Airplane				Tilt Bulldozer				Tilt Airplane			
Subject	Symbols	Order	Location	Total	Symbols	Order	Location	Total	Symbols	Order	Location	Total	Symbols	Order	Location	Total
1	4	4	4	12	4	4	4	12	3	4	3	10	3	4	4	11
2	4	4	4	12	4	4	4	12	3	4	4	11	4	4	4	12
3	3	4	4	11	4	4	3	11	4	4	4	12	3	4	4	11
4	4	4	3	11	4	4	3	11	4	4	4	12	4	2	1	7
5	4	4	2	10	4	4	2	10	4	4	1	9	3	4	1	8
6a	3	4	3	10	4	4	4	12	4	4	4	12	4	4	3	11
7	1	1	4	6	1	2	2	5	3	4	0	7	3	4	4	11
8	4	4	2	10	4	4	2	10	4	4	4	12	3	4	2	9
9	3	1	1	5	4	4	4	12	4	2	2	8	4	4	4	12
10	4	4	2	10	4	4	3	11	4	4	4	12	4	4	4	12
11	4	4	4	12	3	4	4	11	4	4	3	11	4	4	3	11
12	4	2	2	8	4	4	4	12	4	4	4	12	4	4	3	11
13	4	4	4	12	4	4	4	12	3	3	3	9	3	4	2	9
14	4	4	2	10	3	4	1	8	2	2	1	5	3	4	2	9
15	4	4	0	8	4	4	1	9	3	4	2	9	4	4	1	9
16	4	4	4	12	3	4	4	11	4	4	4	12	4	4	4	12
17a	4	4	4	12	4	4	1	9	4	2	2	8	4	4	2	10
18	3	4	2	9	3	2	3	8	3	2	2	7	0	0	3	3
19a	4	4	4	12	4	4	4	12	4	4	4	12	4	4	4	12
20	4	4	4	12	4	4	4	12	4	4	4	12	4	4	3	11
21	4	4	4	12	4	4	4	12	4	4	3	11	3	4	4	11
22	3	4	0	7	4	4	4	12	4	4	4	12	4	4	4	12
23	4	4	4	12	4	4	4	12	4	4	3	11	4	4	4	12
24	4	4	3	11	4	4	3	11	4	4	4	12	4	4	4	12
17	4	4	3	11	4	4	4	12	4	4	1	9	4	4	3	11
19	3	4	4	11	4	4	3	11	4	4	4	12	3	3	1	7
6	4	4	4	12	4	4	3	11	4	4	4	12	4	4	4	12
average	3.67	3.67	2.92	10.25	3.71	3.83	3.17	10.71	3.67	3.63	3.04	10.33	3.50	3.75	3.08	10.33
stdev	0.70	0.92	1.32	2.09	0.69	0.56	1.09	1.78	0.56	0.77	1.20	2.08	0.88	0.90	1.10	2.12

Figure 59: Isometric Joystick Study: Exocentric Memory Task Results

Fly	Bulldozer				Airplane				Tilt Bulldozer				Tilt Airplane			
Subject	Symbols	Order	Location	Total	Symbols	Order	Location	Total	Symbols	Order	Location	Total	Symbols	Order	Location	Total
1	4	4	4	12	4	4	3	11	4	4	3	11	4	4	3	11
2	4	4	4	12	4	4	3	11	2	2	2	6	4	4	3	11
3	4	4	1	9	0	0	2	2	3	2	1	6	4	4	2	10
4	4	4	0	8	4	4	1	9	4	4	0	8	4	4	1	9
5	4	4	1	9	3	4	0	7	3	1	1	5	4	2	0	6
6a	4	2	1	7	4	4	3	11	4	2	2	8	3	4	0	7
7	2	2	1	5	4	4	1	9	2	2	3	7	2	2	0	4
8	3	4	2	9	4	4	4	12	3	4	0	7	4	3	1	8
9	4	4	3	11	4	4	4	12	4	4	1	9	4	3	2	9
10	4	4	2	10	4	4	4	12	4	4	1	9	4	4	4	12
11	4	4	1	9	2	2	3	7	4	4	2	10	1	1	0	2
12	4	4	4	12	4	4	3	11	4	4	3	11	4	4	3	11
13	4	4	2	10	3	0	1	4	4	4	2	10	4	4	1	9
14	3	4	2	9	4	4	2	10	2	2	1	5	3	4	0	7
15	2	0	1	3	4	4	2	10	3	4	2	9	3	2	0	5
16	4	4	1	9	2	2	2	6	3	2	1	6	3	4	3	10
17a	2	0	0	2	3	4	0	7	3	4	1	8	4	4	1	9
18	4	4	1	9	1	1	0	2	3	2	0	5	1	0	0	1
19a	4	4	4	12	4	4	4	12	4	4	3	11	4	4	3	11
20	3	4	1	8	2	2	1	5	4	4	1	9	3	4	4	11
21	4	4	2	10	4	4	4	12	4	4	3	11	4	4	1	9
22	4	4	0	8	4	4	4	12	4	4	3	11	4	4	2	10
23	4	4	2	10	4	4	4	12	3	4	4	11	4	4	3	11
24	4	4	3	11	4	4	3	11	4	4	4	12	4	4	4	12
17	4	4	4	12	3	4	4	11	4	4	2	10	4	4	2	10
19	4	2	2	8	2	0	3	5	3	4	4	11	3	4	2	9
6	4	4	2	10	4	4	3	11	4	4	3	11	4	4	3	11
average	3.63	3.50	1.79	8.92	3.33	3.29	2.42	9.04	3.42	3.29	1.83	8.54	3.46	3.38	1.71	8.54
stdev	0.71	1.22	1.28	2.60	1.13	1.33	1.41	3.26	0.72	1.04	1.20	2.25	0.93	1.13	1.46	3.04

Figure 60: Isometric Joystick Study: Egocentric Memory Task Results

	Bulldozer									Airplane									Tilt Bulldozer									Tilt Airplane								
Subject/Question	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
1	5	1	4	1	2	3	2	1	1	5	5	2	2	5	4	4	4	3	5	3	3	4	2	3	3	3	2	5	4	2	3	2	3	3	3	2
2	2	2	4	2	2	3	2	2	2	5	5	1	5	4	4	4	5	4	3	2	3	2	2	2	3	2	2	5	4	2	4	3	5	4	4	3
3	5	5	3	5	5	4	3	4	5	4	4	3	4	4	2	3	3	3	4	4	3	4	3	3	4	4	4	4	4	3	4	4	3	3	4	4
4	3	2	4	4	2	2	3	3	2	4	4	2	4	5	2	4	4	4	4	4	3	4	4	3	4	4	3	4	4	4	4	3	4	4	4	2
5	4	5	1	4	5	4	4	5	5	4	5	2	5	5	4	4	5	5	5	5	2	4	5	3	5	5	5	4	4	1	4	3	5	4	4	5
6a	2	2	2	3	3	2	2	3	2	5	4	2	3	4	4	3	4	3	4	4	2	3	4	3	4	4	3	4	3	3	3	4	4	3	3	2
7	4	3	4	3	1	4	1	3	2	4	4	4	2	5	4	4	4	3	4	4	4	2	2	2	2	3	2	4	3	4	2	2	3	2	2	2
8	4	3	4	4	4	4	3	3	2	4	4	4	4	4	4	4	4	3	3	3	3	2	3	3	3	3	2	3	3	1	4	4	5	3	3	2
9	4	2	4	3	2	1	4	2	2	4	5	2	5	5	4	4	4	3	5	4	2	4	2	4	4	3	3	5	4	2	4	2	3	4	4	2
10	5	4	2	3	4	3	2	3	3	5	5	1	4	4	4	5	5	5	4	3	1	3	4	3	3	3	3	4	4	2	4	4	4	3	4	4
11	4	3	4	2	4	2	1	3	2	4	4	2	4	4	4	2	3	2	4	4	4	2	4	2	2	3	2	3	3	2	3	4	2	2	4	2
12	4	3	2	4	3	3	4	4	4	4	5	3	4	5	4	4	4	4	4	2	4	2	2	3	2	2	2	4	2	4	2	3	3	2	2	2
13	2	2	3	1	1	2	1	2	1	4	4	2	4	4	3	3	4	3	4	4	2	2	3	3	4	3	4	2	2	3	2	1	2	2	2	2
14	4	3	3	5	4	3	2	4	2	5	4	2	4	4	3	4	4	3	4	3	3	3	4	2	3	3	2	4	3	3	3	2	3	2	3	2
15	4	4	2	5	3	4	3	3	2	5	4	1	4	4	3	4	4	4	5	4	1	5	4	3	4	4	3	5	4	1	5	5	4	4	4	4
16	4	3	3	2	2	2	4	3	1	4	4	2	3	4	2	5	4	1	4	4	2	4	2	2	4	4	1	4	4	2	3	2	2	3	3	1
17a	4	4	2	3	3	2	3	3	3	4	4	3	2	2	3	3	4	3	2	2	3	2	3	2	2	2	2	3	3	3	2	2	2	2	2	2
18	5	4	3	2	4	4	4	4	2	4	4	4	2	3	3	2	3	2	4	4	2	4	4	2	4	4	2	4	4	3	4	4	4	2	3	2
19a	4	4	2	5	5	4	2	4	2	4	4	3	4	4	4	2	4	2	4	2	3	2	2	4	1	3	1	5	4	2	4	4	4	2	4	2
20	3	3	2	3	2	4	2	3	2	4	2	4	4	4	3	2	4	4	4	4	3	4	2	4	2	4	3	4	3	3	3	4	2	2	3	3
21	4	4	3	4	4	4	4	4	3	5	5	2	4	4	4	4	4	3	4	3	3	3	4	3	3	4	2	4	3	3	2	4	3	3	3	2
22	5	3	2	4	3	4	3	3	3	4	5	3	5	5	4	4	4	4	3	2	3	3	2	3	3	2	2	4	3	3	2	3	3	2	3	2
23	5	5	3	2	3	4	4	3	3	5	5	3	3	3	3	2	3	3	5	5	3	3	2	4	3	4	3	5	5	3	2	3	4	4	4	3
24	1	1	4	1	1	2	1	2	2	4	4	2	2	4	4	4	4	4	3	2	2	2	4	4	2	3	2	4	2	3	1	1	4	2	2	2
6	4	3	5	4	4	3	4	4	2	5	4	2	2	4	3	4	4	2	2	1	4	1	2	2	2	2	1	4	2	4	2	3	3	2	2	1
17	4	3	4	4	3	4	4	3	3	4	3	2	3	4	4	2	3	3	4	1	3	1	3	4	1	1	1	4	3	3	3	2	4	3	3	3
19	5	2	4	2	5	2	2	3	2	5	5	2	5	5	3	5	5	2	5	4	4	2	4	2	3	4	2	5	4	3	2	2	2	4	4	2

#of responses

Strongly Disagree	1	2	1	3	3	1	4	1	3	0	0	3	0	0	0	0	0	1	0	0	2	0	0	0	1	0	2	0	0	3	1	2	0	0	0	1
Disagree	3	5	8	5	6	7	7	4	13	0	1	11	5	1	3	5	0	3	1	6	7	9	10	7	6	4	12	1	3	7	7	6	5	11	5	16
Indifferent	2	8	7	6	6	5	6	12	5	0	0	6	3	2	7	4	4	11	4	5	12	6	4	12	8	10	7	3	9	11	6	6	8	7	9	3
Agree	12	6	8	6	6	11	7	6	1	16	14	4	12	14	14	13	17	7	14	11	3	8	9	5	8	9	2	14	11	3	9	9	8	6	10	3
Strongly Agree	6	3	0	4	3	0	0	1	2	8	9	0	4	7	0	2	3	2	5	2	0	1	1	0	1	1	1	6	1	0	1	1	3	0	0	1
total	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
average	3.79	3.13	2.92	3.13	3.00	3.08	2.67	3.08	2.42	4.33	4.29	2.46	3.63	4.13	3.46	3.50	3.96	3.25	3.96	3.38	2.67	3.04	3.04	2.92	3.08	3.29	2.50	4.04	3.42	2.58	3.08	3.04	3.38	2.79	3.21	2.46
stdev	1.10	1.15	0.93	1.30	1.25	0.97	1.09	0.88	1.06	0.48	0.69	0.93	1.01	0.74	0.72	0.93	0.55	0.94	0.75	0.97	0.82	0.95	1.00	0.72	0.97	0.81	0.93	0.75	0.78	0.88	1.02	1.08	0.97	0.83	0.78	0.93

Averages									
Interface/Question	1	2	3	4	5	6	7	8	9
B	3.79	3.13	2.92	3.13	3.00	3.08	2.67	3.08	2.42
A	4.33	4.29	2.46	3.63	4.13	3.46	3.50	3.96	3.25
TB	3.96	3.38	2.67	3.04	3.04	2.92	3.08	3.29	2.50
TA	4.04	3.42	2.58	3.08	3.04	3.38	2.79	3.21	2.46

Figure 61: Isometric Joystick Study: Post-Trial Interface Ratings

Question

Subject	1. Learn B	1. Learn A	1. Learn TB	1. Learn TA	2. Use B	2. Use A	2. Use TB	2. Use TA	3. Errors B	3. Errors A	3. Errors TB	3. Errors TA	4. Fast B	4. Fast A	4. Fast TB	4. Fast TA
1	4	2	1	3	4	1	2	3	1	4	3	2	4	1	2	3
2	4	1	3	2	4	1	3	2	1	4	2	3	4	1	3	2
3	1	2	3	4	1	2	3	4	4	3	2	1	1	2	3	4
4	4	1	2	3	4	1	2	3	1	4	2	3	4	1	2	3
5	1	2	3	4	2	1	3	4	3	2	1	4	2	1	3	4
6a	4	2	1	3	4	1	2	3	1	4	3	2	4	1	2	3
7	3	2	4	1	3	1	4	2	1	4	3	2	2	1	3	4
8	3	1	2	4	3	1	2	4	2	1	4	3	3	1	2	4
9	4	1	3	2	4	1	3	2	1	4	2	3	2	1	4	3
10	1	2	4	3	4	1	2	3	3	4	2	1	4	1	2	3
11	4	3	1	2	4	3	1	2	1	2	3	4	4	3	2	1
12	2	1	4	3	2	1	4	3	3	4	2	1	2	1	4	3
13	1	2	3	4	1	2	3	4	4	3	2	1	2	1	3	4
14	2	1	4	3	3	1	4	2	4	3	1	2	1	2	4	3
15	4	1	3	2	4	2	3	1	1	4	2	3	4	2	1	3
16	1	3	2	4	1	2	3	4	1	4	2	3	3	1	2	4
17 a	2	1	4	3	2	1	4	3	3	4	1	2	2	1	4	3
18	4	1	3	2	4	1	2	3	1	3	2	4	4	1	3	2
19 a	4	2	3	1	2	1	4	3	2	3	1	4	1	2	4	3
20	4	1	3	2	3	2	1	4	3	1	4	2	3	4	1	2
21	2	1	3	4	2	1	3	4	2	1	3	4	2	1	4	3
22	2	1	4	3	2	1	4	3	3	4	1	2	2	1	4	3
23	2	1	4	3	4	1	2	3	3	4	1	2	2	1	3	4
24	4	2	3	1	4	1	3	2	1	4	2	3	4	1	3	2
17	2	1	4	3	2	1	4	3	4	3	1	2	2	1	4	3
19	3	1	4	2	3	1	4	2	1	4	2	3	4	1	3	2
6	2	1	3	4	2	1	4	3	2	4	1	3	2	1	4	3
# of responses for Fourth	11	0	7	6	11	0	6	7	3	14	2	5	9	1	7	7
# of responses for Third	2	2	11	9	4	1	9	10	7	5	5	7	3	1	8	12
# of responses for Second	6	9	3	6	6	5	7	6	3	2	11	8	9	4	7	4
# of responses for First	5	13	3	3	3	18	2	1	11	3	6	4	3	18	2	1
Total # of responses	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Average	2.79	1.54	2.92	2.75	2.96	1.29	2.79	2.96	2.08	3.25	2.13	2.54	2.75	1.38	2.83	3.04
Stdev	1.25	0.66	0.97	0.99	1.12	0.55	0.93	0.86	1.14	1.07	0.90	1.02	1.11	0.77	0.96	0.81
Overall Ranking	3	1	4	2	3	1	2	3	1	4	2	3	2	1	3	4

Subject	5. Precise B	5. Precise A	5. Precise TB	5. Precise TA	6. Remember B	6. Remember A	6. Remember TB	6. Remember TA	7. Comfort B	7. Comfort A	7. Comfort TB	7. Comfort TA	8. Effective B	8. Effective A	8. Effective TB	8. Effective TA	9. Want B	9. Want A	9. Want TB	9. Want TA
1	4	1	2	3	2	1	4	3	4	1	2	3	4	1	2	3	4	1	2	3
2	4	1	3	2	2	4	1	3	2	1	4	3	4	1	3	2	4	1	3	2
3	1	2	3	4	4	1	3	2	1	2	3	4	1	2	3	4	1	2	4	3
4	4	1	2	3	1	4	2	3	4	1	2	3	4	1	2	3	4	1	2	3
5	3	1	2	4	3	4	2	1	2	1	3	4	2	1	3	4	2	1	3	4
6a	4	2	1	3	1	4	3	2	4	1	2	3	4	2	1	3	4	1	2	3
7	4	1	2	3	3	4	1	2	3	1	4	2	3	1	4	2	3	1	4	2
8	3	1	2	4	2	1	3	4	2	1	3	4	3	1	2	4	2	1	3	4
9	3	1	4	2	1	4	3	2	2	1	4	3	4	1	3	2	4	1	3	2
10	4	2	1	3	1	4	3	2	4	1	2	3	3	1	2	4	3	1	2	4
11	1	2	3	4	1	3	4	2	3	2	1	4	4	3	1	2	4	2	1	3
12	2	1	3	4	3	4	1	2	2	1	4	3	2	1	4	3	2	1	4	3
13	2	1	3	4	4	3	1	2	1	2	3	4	1	2	3	4	1	2	3	4
14	1	4	2	3	3	4	1	2	2	1	4	3	1	2	4	3	1	4	2	3
15	4	1	3	2	1	3	2	4	4	2	3	1	4	2	3	1	4	2	3	1
16	1	2	3	4	4	3	2	1	2	4	1	3	1	2	3	4	1	3	2	4
17 a	2	4	3	1	2	1	4	3	2	1	4	3	2	1	4	3	2	1	3	4
18	4	1	2	3	4	1	2	3	4	1	2	3	2	1	4	3	4	1	3	2
19 a	1	2	4	3	4	1	2	3	2	1	4	3	2	1	4	3	2	1	4	3
20	4	1	3	2	3	4	2	1	4	2	3	1	2	4	1	3	2	4	1	3
21	2	1	3	4	3	4	2	1	2	1	3	4	2	1	3	4	2	1	3	4
22	2	1	4	3	3	4	1	2	2	1	4	3	2	1	4	3	2	1	4	3
23	4	1	3	2	3	4	1	2	2	1	4	3	2	1	4	3	2	1	4	3
24	4	1	3	2	1	4	3	2	4	1	3	2	4	1	3	2	4	1	3	2
17	3	4	1	2	3	4	1	2	2	1	4	3	2	1	4	3	2	1	4	3
19	4	1	3	2	1	4	2	3	4	1	3	2	3	1	4	2	3	1	4	2
6	2	1	4	3	2	4	1	3	2	1	4	3	2	1	4	3	2	1	4	3
# of responses for Fourth	11	2	3	8	5	14	3	2	8	1	9	6	8	1	8	7	9	2	6	7
# of responses for Third	3	0	12	9	8	4	6	6	2	0	8	14	3	1	9	11	2	1	10	11
# of responses for Second	5	6	7	6	4	0	8	12	12	5	5	2	9	6	4	5	9	4	6	5
# of responses for First	5	16	2	1	7	6	7	4	2	18	2	2	4	16	3	1	4	17	2	1
Total # of responses	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
Average	2.83	1.50	2.67	3.00	2.46	3.08	2.21	2.25	2.67	1.33	3.00	3.00	2.63	1.46	2.92	3.00	2.67	1.50	2.83	3.00
Stdev	1.24	0.88	0.82	0.88	1.14	1.28	1.02	0.85	1.05	0.70	0.98	0.83	1.13	0.78	1.02	0.83	1.17	0.93	0.92	0.83
Overall Ranking	3	1	2	4	2	1	4	3	2	1	3	3	2	1	3	4	2	1	3	4

Figure 62: Isometric Joystick Study: Post-Experiment Interface Rankings

APPENDIX C

SPATIAL COGNITION STUDIES

The following pages contain copies of materials used during the spatial cognition studies. Some of these materials may be reproduced at smaller than original scale to satisfy dissertation formatting.

Two versions of the Photograph Test are included, one for each series of the spatial cognition studies. The first series was conducted during the fall and the second series was conducted during the spring. New photographs were taken to reflect seasonal changes.

Title	Number of Pages
Spatial Cognition Study: Consent Form	1
Spatial Cognition Study: Pre-Experiment Questionnaire	5
Spatial Cognition Study: Photograph Test for Series 1	30
Spatial Cognition Study: Photograph Test for Series 2	30
Spatial Cognition Study: Photograph Test Form	1
Spatial Cognition Study: Photograph Test Map	1
Spatial Cognition Study: Photograph Test Form Answers	1
Spatial Cognition Study: Photograph Test Map Answers	1
Spatial Cognition Study: Post-Experiment Questionnaire	2
Spatial Cognition Study: First Series Data Summary	1
Spatial Cognition Study: First Series Spatial Rotation Test Results	1
Spatial Cognition Study: First Series Visual Memory Test Results	1
Spatial Cognition Study: First Series Landmark Placement Results	2
Spatial Cognition Study: Second Series, Phase 1 Data Summary	1
Spatial Cognition Study: Second Series, Phase 1 Spatial Rotation Test Results	1
Spatial Cognition Study: Second Series, Phase 1 Visual Memory Test Results	1
Spatial Cognition Study: Second Series, Phase 1 Landmark Placement Results	2
Spatial Cognition Study: Second Series, Phase 2 Data Summary	1
Spatial Cognition Study: Second Series, Phase 2 Spatial Rotation Test Results	1
Spatial Cognition Study: Second Series, Phase 2 Visual Memory Test Results	1
Spatial Cognition Study: Second Series, Phase 2 Landmark Placement Results	2

Table 12: List of Appended Materials from the Spatial Cognition Studies

Wearable Computer Based Overview Imagery and Spatial Cognition
Research Consent Form

Title of Research Study

The title of this study is ìWearable Computer Based Overview Imagery and Spatial Cognition.î

Investigators

David M Krum	Bill Ribarsky
Principal Investigator	Faculty Sponsor
dkrum@cc.gatech.edu	ribarsky@cc.gatech.edu

College of Computing, Georgia Institute of Technology

Purpose of Research

You are being asked to volunteer for a research study to examine wearable computers and their effect on spatial cognition. Spatial cognition is the ability to perceive and understand the spatial layout of an environment. Eligible participants are 18 years or older, have binocular vision, are unfamiliar with the Georgia Tech campus, and can travel an outdoor route on the Georgia Tech campus.

Procedures Used in the Study

Your participation should last approximately two hours.

You will first fill out a questionnaire to allow us to collect some information about your computer experience, navigation experience, and some other demographic information. You will then be asked to take two standard psychology tests concerning visual memory and spatial orientation. Then you will receive instruction about your task. Your task will involve navigating a path on the Georgia Tech campus. You will be randomly ('by chance, like flipping a coiní') assigned a particular type of overview map on a wearable computer, or no overview map at all.

Your task will be to follow a route on the Georgia Tech campus, paying attention to buildings and other landmarks, and learning the campus layout. After completing the task, you will be given two tests to see if you can recall the landmarks and their spatial arrangement. You will also be given a questionnaire about your experience.

Foreseeable Risks from the Study

Since this task involves using an eyeglass mounted display, there are some minor risks of headache and dizziness. There is a small chance of tripping.

Potential Benefits from the Study

There is no direct benefit to you by participating, however we hope that your participation in this study will lead to better computer interfaces for mobile and wearable computers. You may also gain a greater understanding of computer interface technology.

Compensation/Costs

You will receive 1 unit of extra credit for you participation in this study. The effect of that extra credit on your course grade is a decision to be made by the instructor. You will receive no financial compensation for your participation.

Alternative Procedures

Alternative opportunities to receive extra credit are available should you choose not to participate in this experiment. These include reading and reviewing a paper on computer interface technology or writing a report about a particular computer interface technology.

Confidentiality of Records

All information about you, including the questionnaires, computer files, and assessment results will be kept private. Your results will be confidential and will be reported anonymously in any article that this research may generate. All data will be coded and kept in a secured, limited access location. . Your identity will not be revealed in any publication or presentation of the results of this research. However, confidentiality cannot be guaranteed; your personal information may be disclosed if required by law.

Disclosure Statement

The researchers have no financial interests in the results of the study. However, they may publish the results of the study.

Injury/Adverse Reactions

Any injuries or reactions should be reported to David Krum at (404) 894-6710 or Dr. Bill Ribarsky at (404) 894-6148. Neither the Georgia Institute of Technology nor the principal investigator has made provision for payment of costs associated with any injury resulting from participation in this study.

Contact Persons

To make inquiries regarding this study, contact David Krum at (404) 385-0256. His office is Centennial Research Building 375. You may also contact Dr. Bill Ribarsky at (404) 894-6148. His office is Centennial Research Building 371.

Voluntary Participation/Withdrawal

Participation in this study is voluntary. You are free to withdraw from participation at any time. Refusal to participate will involve no penalty or loss of benefits to which the subject is otherwise entitled. Under certain circumstances, participants may be withdrawn from the study without their consent if the researcher decides that it is not in their best interest, or if they fail to follow the procedures. If you wish to withdraw from participation, please tell the researcher at any time.

You have rights as a research volunteer. Taking part in this study is completely voluntary. If you do not take part, you will have no penalty. You may stop taking part in this study at any time with no penalty. If you have any questions about the informed consent document, or the consent process, or your rights as a research volunteer, contact:

Office of Research Compliance
Georgia Institute of Technology
Atlanta, Georgia 30332-0420
Voice (404) 894-6944
Fax (404) 385-0864
irb@gatech.edu

A copy of this form will be given to you.

Your signature below indicates that the researchers have answered all of your questions to your satisfaction and that you consent to volunteer for this study.

______________________________ ________________
Signature of Participant Date

____
Name of Participant (Please Print)

______________________________ ________________
Signature of Investigator Date

Figure 63: Spatial Cognition Study: Consent Form

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

Gender: (circle one) Male Female	Age in years:
Current Profession or Job:	
List degrees earned and majors: ____ ____	
List any degrees and majors in progress: ____	

Vision:	No Vision Correction Contacts Glasses Other: ______________________
Do you have vision in both eyes?	Yes / No
Are you right-handed or left-handed?	Right / Left
Please note any mobility aids you use (wheelchair, cane, etc.):	

Have you visited the Georgia Tech Campus before?	Yes / No
Are you familiar with the layout of the Georgia Tech Campus?	Yes / No
In what class did you hear about this study?	

1/5

Figure 64: Spatial Cognition Study: Pre-Experiment Questionnaire (Page 1 of 5)

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

	Never	Seldom	Sometimes	Frequently	Constantly
Do you use a computer for work? (Word processing, spreadsheets, design, etc.)	1	2	3	4	5
Do you use a computer for entertainment? (Games, chat, etc.)	1	2	3	4	5
Do you play first person 3D computer games such as Quake, Unreal, etc?	1	2	3	4	5
Do you play real time strategy games such as Civilization, Warcraft, Tiberian Sun, etc?	1	2	3	4	5
Do you play aircraft simulator games such as Flight Simulator, Comanche, Falcon, etc?	1	2	3	4	5
Do you use 3D design software like AutoCAD or 3D Studio Max?	1	2	3	4	5
Have you ever used a wearable computer before?	1	2	3	4	5

Name the city, state, and country where you were raised? (Location where you spent the most time between birth and age 18.)	
How would you characterize the place you were raised?	Rural Suburban Urban Other: ______________________

Do you have a GPS (Global Positioning) device?	Yes / No				
How often do you use it?	Never	Seldom	Sometimes	Frequently	Constantly
What are your main uses for your GPS?					

2/5

Figure 65: Spatial Cognition Study: Pre-Experiment Questionnaire (Page 2 of 5)

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

Where you a Boy Scout, Girl Scout, or Explorer?	Yes / No
Did you earn any merit badges involving orienteering or navigation?	Yes / No
Did you earn any merit badges involving small boat sailing?	Yes / No

Have you used a map while driving?	Never	Seldom	Sometimes	Frequently	Constantly
Have you used map and compass for land navigation?	Never	Seldom	Sometimes	Frequently	Constantly
Have you ever piloted a boat on the ocean?	Never	Seldom	Sometimes	Frequently	Constantly
Have you ever piloted a boat on a lake or river?	Never	Seldom	Sometimes	Frequently	Constantly
Have you used charts, compasses, and other devices for navigation on the water?	Never	Seldom	Sometimes	Frequently	Constantly

Do you consider yourself to be a good navigator? Why?

	Never	Once a Year	Once a Month	Once a Week	Once a Day
How often do you find yourself lost?	1	1	2	3	4

When you become lost, how are you traveling?	Car	Bus	Foot	Bicycle	Other (fill in) ___________

3/5

Figure 66: Spatial Cognition Study: Pre-Experiment Questionnaire (Page 3 of 5)

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

What factors cause you to become lost? Please list and describe.

Where do you most often become lost? Please describe one or more locations.

When you are giving directions, do you use:

	Never	Seldom	Sometimes	Frequently	Always
Street names	1	2	3	4	5
Descriptions of buildings, intersections, etc.	1	2	3	4	5
Cardinal directions (i.e. North, East, South, West)	1	2	3	4	5
Distance traveled	1	2	3	4	5
GPS device	1	2	3	4	5
Directions from the Internet (Mapquest or other website)	1	2	3	4	5
A store bought map	1	2	3	4	5
A hand drawn map	1	2	3	4	5
Other: ___________________________	1	2	3	4	5

4/5

Figure 67: Spatial Cognition Study: Pre-Experiment Questionnaire (Page 4 of 5)

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

When you are following directions, these items are helpful to you.

	Never	Seldom	Sometimes	Frequently	Always
Street names	1	2	3	4	5
Descriptions of buildings, intersections, etc.	1	2	3	4	5
Cardinal directions (North, East, South, West)	1	2	3	4	5
Distance traveled	1	2	3	4	5
GPS device	1	2	3	4	5
Directions from the Internet (Mapquest or other website)	1	2	3	4	5
A store bought map	1	2	3	4	5
A hand drawn map	1	2	3	4	5
Other: ___________________________	1	2	3	4	5

5/5

Figure 68: Spatial Cognition Study: Pre-Experiment Questionnaire (Page 5 of 5)

Figure 69: Spatial Cognition Study: Photograph Test for Series 1 (Image 1 of 30)

Figure 70: Spatial Cognition Study: Photograph Test for Series 1 (Image 2 of 30)

Figure 71: Spatial Cognition Study: Photograph Test for Series 1 (Image 3 of 30)

Figure 72: Spatial Cognition Study: Photograph Test for Series 1 (Image 4 of 30)

Figure 73: Spatial Cognition Study: Photograph Test for Series 1 (Image 5 of 30)

Figure 74: Spatial Cognition Study: Photograph Test for Series 1 (Image 6 of 30)

Figure 75: Spatial Cognition Study: Photograph Test for Series 1 (Image 7 of 30)

Figure 76: Spatial Cognition Study: Photograph Test for Series 1 (Image 8 of 30)

Figure 77: Spatial Cognition Study: Photograph Test for Series 1 (Image 9 of 30)

Figure 78: Spatial Cognition Study: Photograph Test for Series 1 (Image 10 of 30)

Figure 79: Spatial Cognition Study: Photograph Test for Series 1 (Image 11 of 30)

Figure 80: Spatial Cognition Study: Photograph Test for Series 1 (Image 12 of 30)

Figure 81: Spatial Cognition Study: Photograph Test for Series 1 (Image 13 of 30)

Figure 82: Spatial Cognition Study: Photograph Test for Series 1 (Image 14 of 30)

Figure 83: Spatial Cognition Study: Photograph Test for Series 1 (Image 15 of 30)

Figure 84: Spatial Cognition Study: Photograph Test for Series 1 (Image 16 of 30)

Figure 85: Spatial Cognition Study: Photograph Test for Series 1 (Image 17 of 30)

Figure 86: Spatial Cognition Study: Photograph Test for Series 1 (Image 18 of 30)

Figure 87: Spatial Cognition Study: Photograph Test for Series 1 (Image 19 of 30)

Figure 88: Spatial Cognition Study: Photograph Test for Series 1 (Image 20 of 30)

Figure 89: Spatial Cognition Study: Photograph Test for Series 1 (Image 21 of 30)

Figure 90: Spatial Cognition Study: Photograph Test for Series 1 (Image 22 of 30)

Figure 91: Spatial Cognition Study: Photograph Test for Series 1 (Image 23 of 30)

Figure 92: Spatial Cognition Study: Photograph Test for Series 1 (Image 24 of 30)

Figure 93: Spatial Cognition Study: Photograph Test for Series 1 (Image 25 of 30)

Figure 94: Spatial Cognition Study: Photograph Test for Series 1 (Image 26 of 30)

Figure 95: Spatial Cognition Study: Photograph Test for Series 1 (Image 27 of 30)

Figure 96: Spatial Cognition Study: Photograph Test for Series 1 (Image 28 of 30)

Figure 97: Spatial Cognition Study: Photograph Test for Series 1 (Image 29 of 30)

Figure 98: Spatial Cognition Study: Photograph Test for Series 1 (Image 30 of 30)

Figure 99: Spatial Cognition Study: Photograph Test for Series 2 (Image 1 of 30)

Figure 100: Spatial Cognition Study: Photograph Test for Series 2 (Image 2 of 30)

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Figure 101: Spatial Cognition Study: Photograph Test for Series 2 (Image 3 of 30)

Figure 102: Spatial Cognition Study: Photograph Test for Series 2 (Image 4 of 30)

Figure 103: Spatial Cognition Study: Photograph Test for Series 2 (Image 5 of 30)

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Figure 104: Spatial Cognition Study: Photograph Test for Series 2 (Image 6 of 30)

Figure 105: Spatial Cognition Study: Photograph Test for Series 2 (Image 7 of 30)

Figure 106: Spatial Cognition Study: Photograph Test for Series 2 (Image 8 of 30)

Figure 107: Spatial Cognition Study: Photograph Test for Series 2 (Image 9 of 30)

Figure 108: Spatial Cognition Study: Photograph Test for Series 2 (Image 10 of 30)

Figure 109: Spatial Cognition Study: Photograph Test for Series 2 (Image 11 of 30)

Figure 110: Spatial Cognition Study: Photograph Test for Series 2 (Image 12 of 30)

Figure 111: Spatial Cognition Study: Photograph Test for Series 2 (Image 13 of 30)

Figure 112: Spatial Cognition Study: Photograph Test for Series 2 (Image 14 of 30)

Figure 113: Spatial Cognition Study: Photograph Test for Series 2 (Image 15 of 30)

Figure 114: Spatial Cognition Study: Photograph Test for Series 2 (Image 16 of 30)

Figure 115: Spatial Cognition Study: Photograph Test for Series 2 (Image 17 of 30)

Figure 116: Spatial Cognition Study: Photograph Test for Series 2 (Image 18 of 30)

Figure 117: Spatial Cognition Study: Photograph Test for Series 2 (Image 19 of 30)

Figure 118: Spatial Cognition Study: Photograph Test for Series 2 (Image 20 of 30)

Figure 119: Spatial Cognition Study: Photograph Test for Series 2 (Image 21 of 30)

Figure 120: Spatial Cognition Study: Photograph Test for Series 2 (Image 22 of 30)

Figure 121: Spatial Cognition Study: Photograph Test for Series 2 (Image 23 of 30)

Figure 122: Spatial Cognition Study: Photograph Test for Series 2 (Image 24 of 30)

Figure 123: Spatial Cognition Study: Photograph Test for Series 2 (Image 25 of 30)

Figure 124: Spatial Cognition Study: Photograph Test for Series 2 (Image 26 of 30)

Figure 125: Spatial Cognition Study: Photograph Test for Series 2 (Image 27 of 30)

Figure 126: Spatial Cognition Study: Photograph Test for Series 2 (Image 28 of 30)

Figure 127: Spatial Cognition Study: Photograph Test for Series 2 (Image 29 of 30)

Figure 128: Spatial Cognition Study: Photograph Test for Series 2 (Image 30 of 30)

Wearable Computer Based Overview Imagery and Spatial Cognition
Route Images

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions : 1. For each image, circle Yes if it could have been seen during your travel. Circle No if it could not.
2. For each image that was seen in your travel, imagine where the picture was taken from. Mark an X on the map indicating that position. Write the image number next to that X. You can use more than one map if you need the room.

Image	Could be Seen?		Image	Could be Seen?		Image	Could be Seen?	
1.	Yes	No	11.	Yes	No	21.	Yes	No
2.	Yes	No	12.	Yes	No	22.	Yes	No
3.	Yes	No	13.	Yes	No	23.	Yes	No
4.	Yes	No	14.	Yes	No	24.	Yes	No
5.	Yes	No	15.	Yes	No	25.	Yes	No
6.	Yes	No	16.	Yes	No	26.	Yes	No
7.	Yes	No	17.	Yes	No	27.	Yes	No
8.	Yes	No	18.	Yes	No	28.	Yes	No
9.	Yes	No	19.	Yes	No	29.	Yes	No
10.	Yes	No	20.	Yes	No	30.	Yes	No

Figure 129: Spatial Cognition Study: Photograph Test Form

For each image that was seen in your travel, imagine where the picture was taken from. Mark an X on the map indicating that position. Write the image number next to that X . You can use more than one map if you need the room.

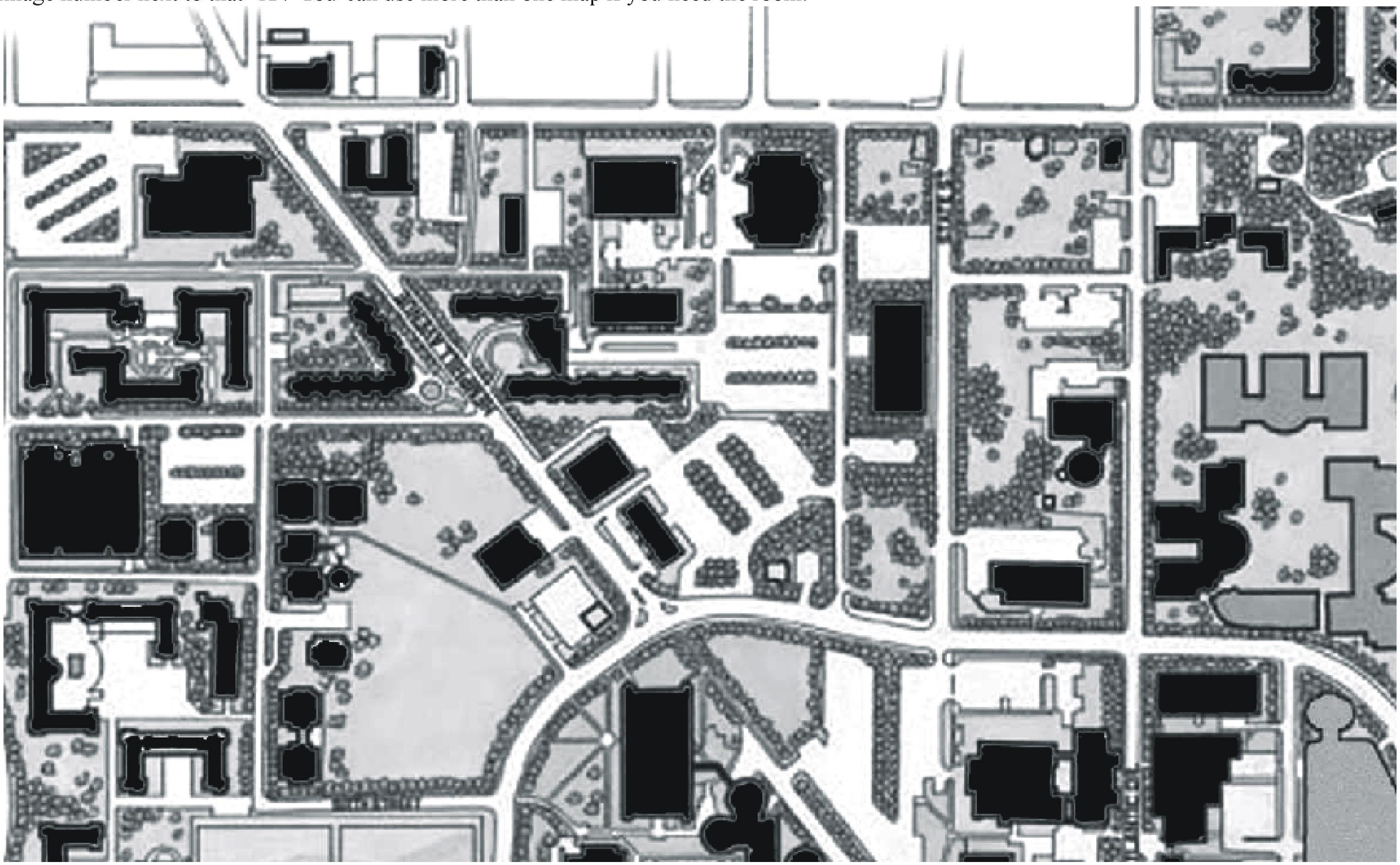

Figure 130: Spatial Cognition Study: Photograph Test Map

Wearable Computer Based Overview Imagery and Spatial Cognition
Route Images

Subject: Answers	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: 1. For each image, circle Yes if it could have been seen during your travel. Circle No if it could not.
2. For each image that was seen in your travel, imagine where the picture was taken from. Mark an X on the map indicating that position. Write the image number next to that X. You can use more than one map if you need the room.

Image	Could be Seen?		Image	Could be Seen?		Image	Could be Seen?	
1.	**Yes**	No	11.	Yes	**No**	21.	**Yes**	No
2.	Yes	**No**	12.	**Yes**	No	22.	**Yes**	No
3.	**Yes**	No	13.	Yes	**No**	23.	**Yes**	No
4.	**Yes**	No	14.	Yes	**No**	24.	**Yes**	No
5.	**Yes**	No	15.	**Yes**	No	25.	Yes	**No**
6.	Yes	**No**	16.	**Yes**	No	26.	**Yes**	No
7.	**Yes**	No	17.	**Yes**	No	27.	Yes	**No**
8.	**Yes**	No	18.	Yes	**No**	28.	**Yes**	No
9.	Yes	**No**	19.	**Yes**	No	29.	Yes	**No**
10.	**Yes**	No	20.	**Yes**	No	30.	**Yes**	No

Figure 131: Spatial Cognition Study: Photograph Test Form Answers

For each image that was seen in your travel, imagine where the picture was taken from. Mark an X on the map indicating that position. Write the image number next to that X. You can use more than one map if you need the room.

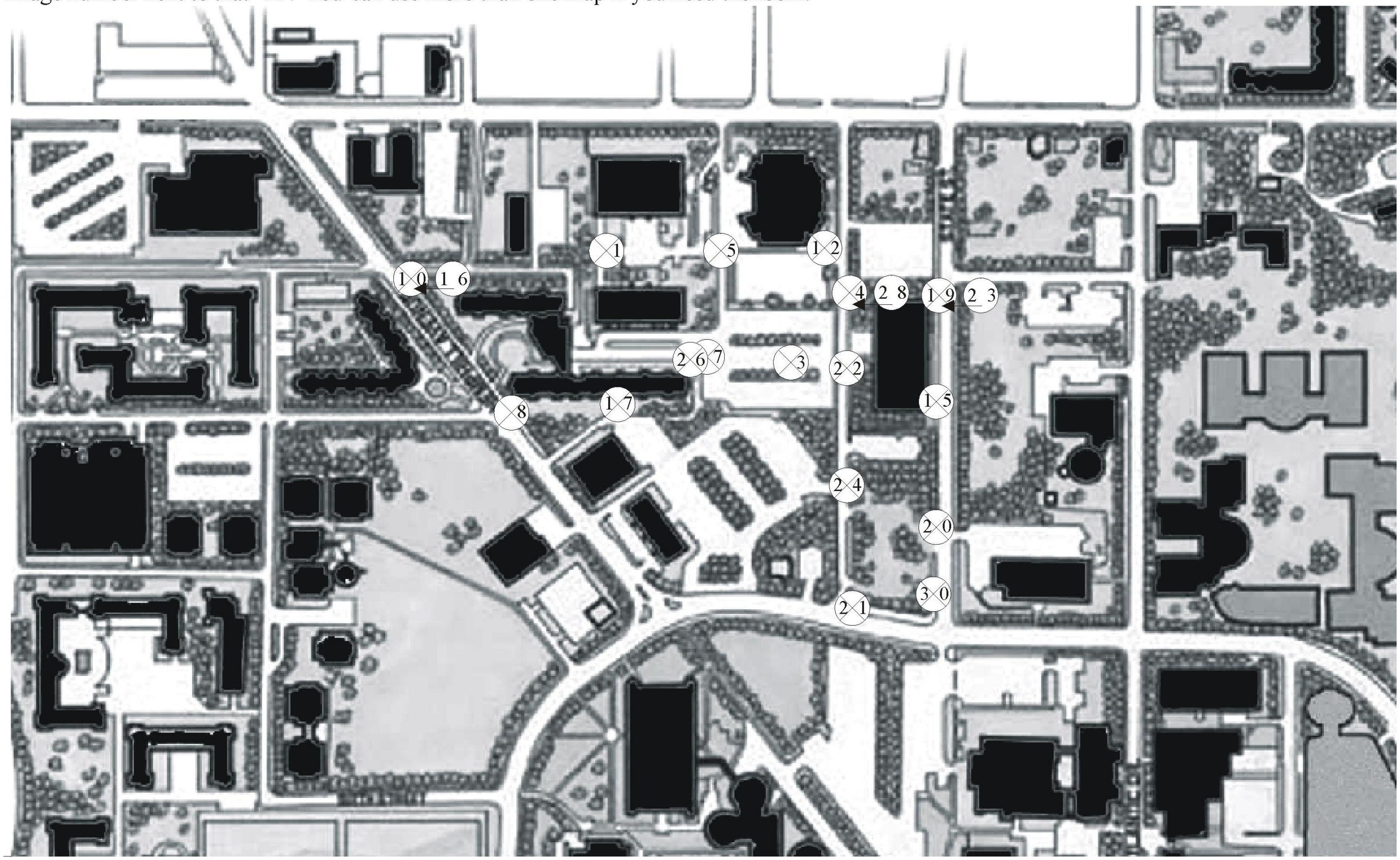

Figure 132: Spatial Cognition Study: Photograph Test Map Answers

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

1. In the test where you examined photographs, did you have any difficulties in determining the photograph location? Explain the difficulties, if any.

2. Do you have any suggestions for things that would have helped you in the photograph test?

3. In the test where you wrote directions, did you have any difficulties? Explain the difficulties, if any.

4. Do you have any suggestions for things that would have helped you in the directions test?

Figure 133: Spatial Cognition Study: Post-Experiment Questionnaire (Page 1 of 2)

Wearable Computer Based Overview Imagery and Spatial Cognition

Subject:	Indoor Outdoor	Map No Map	North Body Head	Overhead Perspective

Instructions: Read and answer the questions below.

5. If you used the wearable computer, did you find the navigation display helpful? Explain.

6. If you used the wearable computer, how might the navigation display be improved?

7. If you used the wearable computer, did you have any difficulties with the wearable computer? Explain.

8. Do you have any other comments about the experiment?

Figure 134: Spatial Cognition Study: Post-Experiment Questionnaire (Page 2 of 2)

Subject	Orientation	Viewpoint	S Total	MV Total	Average Landmark Offset Error (50th's of an inch)	Recognition Errors (out of 30)
500	North	Overhead	68.57	88.19	4.283	12
501	Head	Overhead	45.49	54.86	7.097	8
502	Head	Perspective	44.17	67.36	1.104	11
503	Body	Overhead	47.6	50.69	4.818	7
504	Body	Perspective	39.51	52.78	16.743	11
505	North	Overhead	42.54	70.14	4.883	6
506	No Map	No Map	62.01	65.97	2.283	4
508	Head	Overhead	45.67	54.17	1.456	7
509	Head	Perspective	39.36	62.85	1.967	11
510	No Map	No Map	25.58	37.5	11.617	9
511	Body	Perspective	47.96	52.08	9.817	11
512	Body	Overhead	52.86	36.11	6.407	7
513	Head	Overhead	33.14	50	6.684	12
514	Head	Perspective	9.76	43.75	14.522	10
515	Body	Overhead	38.11	54.17	2.803	6
516	No Map	No Map	29.06	59.72	10.375	5
517	Body	Perspective	18.62	47.22	4.893	12
518	Body	Overhead	12.93	36.81	13.924	8
520	Head	Overhead	51.61	59.72	2.82	10
521	Head	Perspective	31.21	71.53	1.491	7
522	Head	Perspective	28.81	65.28	15.898	10
523	No Map	No Map	57.69	69.44	1.129	9
524	No Map	No Map	72.28	62.5	3.101	8
525	No Map	No Map	47.22	46.53	3.982	9
526	Body	Perspective	42.98	78.47	2.611	7
527	Body	Overhead	44.42	52.08	2.692	8
528	No Map	No Map	58.13	92.36	8.394	7
529	Head	Overhead	61.25	89.58	N/A	7
530	No Map	No Map	59.88	48.61	0.915	2
531	No Map	No Map	36.03	52.08	0.691	3
532	Body	Perspective	45.03	72.22	5.624	10
534	No Map	No Map	16.52	40.97	16.953	7
535	No Map	No Map	52.23	12.5	4.154	8
536	Head	Overhead	58.07	75.69	1.367	9
538	North	Overhead	45.15	18.06	8.843	8
539	No Map	No Map	54.75	56.94	19.463	12
540	North	Overhead	34.99	89.93	3.187	5
542	No Map	No Map	69.33	72.22	1.2	7
543	No Map	No Map	33.87	69.44	11.519	10
544	No Map	No Map	21.25	60.42	14.673	12
545	North	Overhead	77.08	68.75	7.037	5

Figure 135: Spatial Cognition Study: First Series Data Summary

First Series Spatial Rotation Scores

from: EKSTROM, R., FRENCH, J., HARMAN, H., and DERMEN, D., Manual for Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service, NR 150 329, 1976.

Participant	S1 (Part 1, 160 questions, 2D rotations)				S2 (Part 2, 42 questions, 3D rotations)				S Total
Number	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	%
500	140	6	128	80.00	42	9	24	57.14	68.57
501	79	1	77	48.13	34	8	18	42.86	45.49
502	90	1	88	55.00	20	3	14	33.33	44.17
503	111	6	99	61.88	42	14	14	33.33	47.60
504	121	3	115	71.88	39	18	3	7.14	39.51
505	91	6	79	49.38	31	8	15	35.71	42.54
506	113	3	107	66.88	42	9	24	57.14	62.01
507	118	0	118	73.75	25	3	19	45.24	59.49
508	93	2	89	55.63	33	9	15	35.71	45.67
509	79	7	65	40.63	30	7	16	38.10	39.36
510	125	33	59	36.88	38	16	6	14.29	25.58
511	133	5	123	76.88	42	17	8	19.05	47.96
512	122	5	112	70.00	35	10	15	35.71	52.86
513	103	8	87	54.38	27	11	5	11.90	33.14
514	72	28	16	10.00	34	15	4	9.52	9.76
515	113	26	61	38.13	42	13	16	38.10	38.11
516	103	5	93	58.13	42	21	0	0.00	29.06
517	87	8	71	44.38	35	19	-3	-7.14	18.62
518	159	55	49	30.63	42	22	-2	-4.76	12.93
519	51	1	49	30.63	21	5	11	26.19	28.41
520	120	6	108	67.50	31	8	15	35.71	51.61
521	89	6	77	48.13	22	8	6	14.29	31.21
522	100	2	96	60.00	41	21	-1	-2.38	28.81
523	99	1	97	60.63	39	8	23	54.76	57.69
524	119	1	117	73.13	42	6	30	71.43	72.28
525	121	4	113	70.63	42	16	10	23.81	47.22
526	100	6	88	55.00	33	10	13	30.95	42.98
527	97	6	85	53.13	25	5	15	35.71	44.42
528	118	6	106	66.25	41	10	21	50.00	58.13
529	120	2	116	72.50	29	4	21	50.00	61.25
530	110	3	104	65.00	35	6	23	54.76	59.88
531	83	1	81	50.63	15	3	9	21.43	36.03
532	110	2	106	66.25	22	6	10	23.81	45.03
534	64	17	30	18.75	20	7	6	14.29	16.52
535	122	6	110	68.75	21	3	15	35.71	52.23
536	104	1	102	63.75	30	4	22	52.38	58.07
537	131	1	129	80.63	42	13	16	38.10	59.36
538	132	9	114	71.25	38	15	8	19.05	45.15
539	117	9	99	61.88	42	11	20	47.62	54.75
540	53	1	51	31.88	28	6	16	38.10	34.99
541	118	7	104	65.00	42	9	24	57.14	61.07
542	123	2	119	74.38	31	2	27	64.29	69.33
543	132	8	116	72.50	40	21	-2	-4.76	33.87
544	94	13	68	42.50	32	16	0	0.00	21.25
545	160	10	140	87.50	42	7	28	66.67	77.08

Figure 136: Spatial Cognition Study: First Series Spatial Rotation Test Results

First Series Visual Memory Scores

from: EKSTROM, R., FRENCH, J., HARMAN, H., and DERMEN, D., Manual for Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service, NR 150 329, 1976.

Participant	MV1 (Part 1, 32 questions, Shape Memory)				MV2 (Part 2, 24 questions, Building Memory)				MV3 (Part 3, 24 questions, Map Memory)				MV Total
Number	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	%
500	32	3	26	81.25	-2	58	22	91.67	24	1	22	91.67	88.19
501	32	7	18	56.25	6	50	10	41.67	24	4	16	66.67	54.86
502	32	9	14	43.75	10	46	20	83.33	24	3	18	75.00	67.36
503	32	13	6	18.75	18	38	20	83.33	24	6	12	50.00	50.69
504	32	4	24	75.00	0	56	13	54.17	23	8	7	29.17	52.78
505	32	5	22	68.75	2	54	12	50.00	24	1	22	91.67	70.14
506	32	7	18	56.25	6	50	20	83.33	24	5	14	58.33	65.97
507	32	3	26	81.25	-2	58	24	100.00	24	0	24	100.00	93.75
508	32	10	12	37.50	12	44	16	66.67	24	5	14	58.33	54.17
509	31	4	23	71.88	1	54	8	33.33	24	2	20	83.33	62.85
510	32	10	12	37.50	12	44	6	25.00	24	6	12	50.00	37.50
511	32	7	18	56.25	6	50	10	41.67	24	5	14	58.33	52.08
512	32	10	12	37.50	12	44	-3	-12.50	24	2	20	83.33	36.11
513	32	12	8	25.00	16	40	16	66.67	24	5	14	58.33	50.00
514	32	7	18	56.25	6	50	0	0.00	24	3	18	75.00	43.75
515	32	10	12	37.50	12	44	10	41.67	24	2	20	83.33	54.17
516	32	6	20	62.50	4	52	8	33.33	24	2	20	83.33	59.72
517	32	12	8	25.00	16	40	8	33.33	24	2	20	83.33	47.22
518	32	7	18	56.25	6	50	-3	-12.50	24	4	16	66.67	36.81
519													
520	32	2	28	87.50	-4	60	6	25.00	24	4	16	66.67	59.72
521	32	7	18	56.25	6	50	20	83.33	24	3	18	75.00	71.53
522	32	2	28	87.50	-4	60	10	41.67	24	4	16	66.67	65.28
523	32	4	24	75.00	0	56	10	41.67	24	1	22	91.67	69.44
524	32	2	28	87.50	-4	60	4	16.67	24	2	20	83.33	62.50
525	32	7	18	56.25	6	50	2	8.33	24	3	18	75.00	46.53
526	32	5	22	68.75	2	54	18	75.00	24	1	22	91.67	78.47
527	32	7	18	56.25	6	50	4	16.67	24	2	20	83.33	52.08
528	32	1	30	93.75	-6	62	22	91.67	24	1	22	91.67	92.36
529	32	3	26	81.25	-2	58	21	87.50	24	0	24	100.00	89.58
530	32	10	12	37.50	12	44	14	58.33	24	6	12	50.00	48.61
531	32	11	10	31.25	14	42	18	75.00	24	6	12	50.00	52.08
532	32	4	24	75.00	0	56	16	66.67	24	3	18	75.00	72.22
534	32	7	18	56.25	6	50	4	16.67	24	6	12	50.00	40.97
535	32	12	8	25.00	16	40	-6	-25.00	23	7	9	37.50	12.50
536	32	3	26	81.25	-2	58	13	54.17	24	1	22	91.67	75.69
537	32	2	28	87.50	-4	60	9	37.50	24	1	22	91.67	72.22
538	32	6	20	62.50	4	52	-8	-33.33	24	9	6	25.00	18.06
539	32	6	20	62.50	4	52	8	33.33	24	3	18	75.00	56.94
540	31	3	25	78.13	-1	56	22	91.67	24	0	24	100.00	89.93
541	32	4	24	75.00	0	56	19	79.17	23	4	15	62.50	72.22
542	32	0	32	100.00	-8	64	6	25.00	24	1	22	91.67	72.22
543	32	2	28	87.50	-4	60	15	62.50	24	5	14	58.33	69.44
544	32	5	22	68.75	2	54	8	33.33	23	2	19	79.17	60.42
545	32	3	26	81.25	-2	58	10	41.67	24	2	20	83.33	68.75

Figure 137: Spatial Cognition Study: First Series Visual Memory Test Results

Subject	1			3			4			5			7		
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	21.3	21.7	1	27.9	17.7	1	30	20.2	1	25.4	21.7	1	24.9	17.9
500	1	25.7	22.3	1	24.9	16.8	1	25.5	23	0			0		
501	1	26.4	25.7	1	21.3	15.6	0			0			0		
502	1	22.9	22.2	1	25.2	17.6	0			0			0		
503	1	24.1	21.9	1	25.9	17.8	0			1	25.6	22.6	1	28.3	18
504	1	35.9	23.7	1	5.1	6.1	1	21.1	7.9	1	3.1	10.3	1	25.7	24.5
505	1	32	22.3	1	24.7	18	0			1	29.6	22.5	0		
506	1	25.2	22.3	1	25.5	18.1	1	29.8	17.1	1	25.4	23.3	1	25.1	17.9
508	1	22.5	22	1	29	17	1	29.7	12.8	0			0		
509	1	25.4	21.8	1	25.2	18.3	0			0			0		
510	1	12.2	18.2	1	5.2	20.3	0			1	25.7	23.3	1	15	17.3
511	1	19.1	14.5	0			1	20	12.8	0			0		
512	1	22.6	22.1	1	16.6	19.2	0			0			1	26.7	21.1
513	1	26	23.7	1	20.4	18.4	1	29.3	18.4	1	27.7	19	1	29.4	23.3
514	1	42.8	11.3	1	42.2	2.6	1	42.5	5.7	0			1	43.7	7.4
515	1	26.5	17.8	1	24.8	17.9	0			1	25.7	23.9	1	31	22.1
516	1	25.5	26.6	1	9.4	15.9	1	17	15.9	1	25.8	22.2	0		
517	1	26	23.4	1	28.6	19.2	1	29.7	18.8	0			0		
518	1	33.4	21.3	1	40.4	18	1	40.4	13.8	0			0		
520	1	22.6	30.1	1	24.7	17.8	0			1	25.7	21.7	0		
521	1	21.9	21.5	1	20.8	17.8	0			0			1	25.7	19.1
522	1	8.7	15.8	1	13	20.7	0			0			1	9.7	18.3
523	1	23.5	21.7	1	25.4	18	1	29.9	18.8	0			1	25.5	18.2
524	1	21.9	22.2	1	28.8	15.7	0			0			1	23.7	13.4
525	1	27.2	21.4	1	24.5	18.2	1	29.4	16	0			1	22.8	18.1
526	1	22.7	22.2	1	27.2	17.9	0			1	25.5	21.5	0		
527	1	22.6	21.5	1	25.3	17.8	0			1	25.5	22.1	1	26.4	20.5
528	1	28.5	20.2	1	14.7	21.8	1	25.2	21.5	0			0		
529	0			0			0			0			0		
530	1	22.5	21.9	1	25.3	17.8	1	29.5	17.8	1	25	22.1	1	25.5	19.2
531	1	21.9	21.9	1	26.9	18.2	1	30	19.6	1	25.8	23.8	0		
532	1	24.9	27.4	1	26.7	18	1	33.4	17.4	1	27.3	26.2	0		
534	1	46.2	7.2	1	41.3	14.6	1	40.2	12.1	1	45.8	5.7	0		
535	1	29.1	18.9	1	22.4	18.7	0			1	25.7	23.8	0		
536	0			0			0			0			0		
537	1	29.6	23.4	1	11.3	26.2	1	9.2	13.6	1	9.5	23.1	1	44.9	12.1
538	1	19.6	9.1	1	18	21.1	1	20.9	18.1	0			0		
539	1	22.4	8.2	1	9.2	9.1	0			0			1	9.4	13.1
540	1	23	22.3	1	24.2	13.8	1	29.7	18.6	1	25.6	22.1	1	27.1	21.2
541	1	25.3	24	1	16.3	19	1	32.8	8.4	1	30.6	23.9	1	28.8	20.3
542	1	25.4	21.9	0			0			0			0		
543	1	9.4	13	1	15.9	2.2	1	33.5	12.9	0			1	27.9	9.1
544	1	-0.6	12.9	1	18	18.5	0			0			0		
545	1	24.8	22	1	24.2	18.2	1	14.5	21	1	25.9	23.6	1	26.3	21.5

Subject	8			10			12			15			16		
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	17.9	15.9	1	14.3	20.7	1	29.1	21.8	1	33.1	16.3	1	14.3	20.7
500	1	17.3	16	0			0			0			0		
501	0			1	19	14.4	0			0			1	20.7	23.3
502	1	17.4	15.8	0			0			1	33.5	16.9	0		
503	1	33.5	8.8	0			1	33.4	12.7	0			1	14	21.3
504	0			0			1	13.7	21.1	1	38.9	12.9	0		
505	0			1	14.4	21.1	1	33.5	20.9	1	40	5.8	0		
506	1	15.8	15.6	0			1	29.5	21.6	1	33.8	15	1	14.8	20.6
508	1	17.3	16	1	15.1	20.5	1	29.7	21.6	0			1	31.3	8.7
509	1	17.5	16.3	0			0			1	33.1	14.9	0		
510	1	21.3	6.8	1	19.2	11.6	1	18.9	21.2	1	36.8	16.7	1	32.4	21.8
511	1	25.4	21.9	0			1	16.4	21.3	1	30.2	23.1	0		
512	1	15.2	16.9	0			0			1	39.1	13.6	1	12.9	22
513	0			0			0			1	36.2	14.5	1	11.9	23
514	0			0			1	37.3	7.8	0			0		
515	1	15.4	20.1	0			1	28.5	21.4	1	31	20.8	0		
516	1	20.3	12.6	0			1	13.5	21.2	1	29.8	17.9	1	10.1	26.5
517	0			0			1	31.7	8.2	1	38.9	12.5	1	28.8	9
518	1	39	7.9	1	40.4	8.6	0			1	27.7	23.4	1	29.9	26.7
520	1	17.6	16.4	0			0			0			1	14.4	20.9
521	1	18.1	15.8	0			1	29.5	21.6	1	33.4	11.9	1	14.1	20.9
522	0			1	12.1	15.7	0			1	10.2	19.9	1	18.4	17.8
523	0			1	13.8	20.8	1	29.3	21.5	0			0		
524	1	20.6	11.9	1	19.7	14.2	0			1	29.8	15.3	1	30	9.3
525	1	15.6	16.8	0			0			1	38.4	14	0		
526	0			0			1	29.8	13.9	1	33.3	11.2	0		
527	1	17.9	16.1	0			0			1	33.5	18.1	0		
528	1	17.2	20.9	0			1	26.6	21.5	1	20.8	26.1	1	24.3	25.4
529	0			0			0			0			0		
530	1	17.8	15.8	1	14.3	21	0			1	33.5	15.3	1	13	22
531	1	18.1	16.1	1	14.5	21.2	1	29.2	22.2	1	33.2	16.6	0		
532	1	34.5	9.3	0			1	29.3	21.9	0			1	21.6	16.2
534	1	40.2	14.3	1	48.3	6.4	0			0			1	49.9	8.4
535	1	17.3	23.1	1	21.6	22	0			1	36.8	15.9	0		
536	0			0			0			0			0		
537	1	25.9	2.3	1	23.5	13.5	1	40.6	19	1	39	12.7	1	24.1	9
538	1	22.1	14.9	1	24.7	11.6	0			1	22.9	13.8	1	24	12.4
539	0			0			0			0			0		
540	1	17.7	16.1	0			1	30	9.1	1	33.3	10.8	1	14.6	20.8
541	0			0			0			1	9.4	8.2	1	40.1	23.8
542	1	17.4	16.8	0			1	29.3	21.2	0			0		
543	0			1	21.2	6.9	0			0			1	18.9	4.6
544	1	25.4	12	0			0			1	16.4	16	0		
545	1	15	19.2	1	17	18	1	29.8	17.7	1	29.7	19.3	1	10.2	26.4

Subject	17			19			20			21			22		
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	21.7	16.2	1	33.2	20.1	1	33.1	11.8	1	30.1	8.9	1	29.9	17.5
500	1	22.1	16.2	0			0			0			1	24.6	22
501	1	18.2	20.7	0			1	24.7	17.3	1	33.4	20.6	1	21.4	21.5
502	1	21.9	15.5	1	33.5	21	0			0			1	29.7	17.4
503	1	20.8	15.9	0			0			1	29.7	21.6	1	29.8	17.8
504	0			0			1	21	14.7	0			1	9.8	8.6
505	1	21	16	1	36.4	20.8	0			1	33.4	8.1	1	28.5	18.1
506	1	25.1	17.9	1	33.9	12.6	0			0			1	28.9	17.9
508	1	23.1	15.8	0			0			1	27.7	9.2	1	29.7	17.1
509	0			1	33.1	20.2	0			0			1	27.3	17.3
510	1	17.8	18.2	1	13	26.6	1	24.4	26.6	0			1	6.9	15.6
511	0			1	21.9	11.2	1	21.4	12.4	1	13.8	21	1	22.8	14.7
512	1	33	20.4	0			0			0			1	17.8	18.5
513	0			1	30.6	20.1	0			0			0		
514	1	33.7	8	0			1	33.6	11.1	0			1	40.3	11.3
515	1	20.9	16	0			0			1	29.9	8.7	1	28.4	18
516	1	9.4	14.1	0			0			1	29.8	23.7	1	9.4	17.7
517	1	32.4	8.4	0			0			0			1	29.2	19.5
518	0			0			0			0			1	40.6	22.7
520	1	33.4	20.3	0			0			1	30.2	8.9	1	29.4	17.7
521	1	23.7	15.8	1	33.4	20.6	0			1	30	9.1	1	29.9	17.2
522	0			1	11	22.6	1	15.7	21.1	0			1	11.4	20.1
523	0			0			0			0			1	29.8	17.5
524	1	21.4	12.7	0			0			1	29.1	8.4	1	28.8	15.7
525	1	21.8	16.5	1	31.8	18.2	0			0			1	28	17.5
526	1	21.8	16	0			1	32.9	8.1	0			1	29.6	12.6
527	1	24.7	16	0			0			0			1	25.7	18.9
528	1	20.4	22.5	0			0			0			1	24.5	23.4
529	0			0			0			0			0		
530	1	21.3	16.2	1	33.2	20.4	0			1	29.7	9.2	1	29.4	18.8
531	1	23.3	15.1	1	33.2	19.6	1	33.1	12.1	1	30.1	9.5	1	30.2	17.2
532	0			0			1	23.7	21.6	0			0		
534	1	47.3	7	1	33.2	16.8	0			0			1	40	17.5
535	1	18.3	20.5	0			1	33.4	14.6	1	30.2	8.7	1	27.6	16.4
536	0			0			1	33.4	13.1	0			1	29.8	17.3
537	1	44.9	12.1	1	29.6	17.7	1	5.5	14	1	33	7.7	1	5.9	2.2
538	1	20.9	18.1	0			0			0			1	25.6	11.1
539	1	9.2	15.8	0			1	9.1	21.2	0			1	9.3	2.5
540	1	20.6	16.1	1	33.4	19.5	0			1	29.4	21.5	1	29.9	17.5
541	1	17.9	21	0			1	21.8	17.9	1	9.5	26.1	1	29.5	17
542	1	24.4	15.9	0			0			0			1	29.7	17.3
543	1	33.3	18.3	0			1	29.4	3.5	0			1	9	2.2
544	0			0			0			0			0		
545	1	19.9	21.2	1	30.9	18.9	1	16	26.5	0			1	21.7	22.2

Subject	23			24			26			28			30			Total
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y	
Key	1	33.2	20.1	1	29.9	13.3	1	24.3	17.8	1	30	20.2	1	33	9.4	20
500	0			0			1	15.5	20.3	0			0			7
501	0			1	14.1	20.4	1	24.6	16.8	0			1	33.3	8.3	11
502	0			1	29.7	14.5	0			0			1	33.5	8.3	9
503	1	29.3	13	1	29.2	16.4	1	24.6	16.8	0			0			13
504	0			1	6.3	15.2	0			0			0			10
505	1	33.3	13.6	0			0			1	35.5	20.8	1	39.7	8	13
506	1	33.1	19.5	1	29.8	19.3	1	24.7	16.8	0			1	33	8.3	16
508	0			1	29.6	14.9	1	24.5	17.8	0			1	33.3	10.1	13
509	0			1	33.7	10.7	1	24.7	17.2	0			1	33	8.6	9
510	1	20.4	26.6	0			1	20	20	1	11.3	24.7	1	35.4	24.3	17
511	0			1	29.3	13.2	0			0			1	29.4	8.7	11
512	1	33.6	14.4	1	33.7	27.1	1	29.7	20.2	0			1	33.5	8.7	12
513	0			0			0			0			1	9.8	26.5	9
514	0			1	30.5	14.8	0			0			0			9
515	0			1	29.7	16.5	1	25	16.8	1	31.6	20.1	1	33.4	10	14
516	1	29.8	4.6	1	9.3	19.6	1	10.5	20.9	1	29.8	19.5	1	29.8	9.2	16
517	0			1	29.2	17	0			0			1	33.5	10.2	10
518	1	41.3	7.7	1	30.4	8.5	1	43.9	11.3	0			1	37.7	26.6	12
520	0			1	30	15.1	0			0			1	33.6	8.9	10
521	0			1	30	11.2	1	24.8	17.5	0			1	33.2	8.6	14
522	0			1	11.4	18.6	0			0			1	14.1	20.5	11
523	1	33.2	19.9	1	29.9	15.5	1	24.7	16.5	0			1	33	8.5	11
524	0			1	29.1	16.3	0			0			1	30.2	8.3	12
525	1	15.3	18.8	1	29.8	13.6	0			0			1	32.9	8.4	12
526	0			1	29.7	11.8	0			0			1	33.2	9.6	10
527	1	33.5	15.6	0			1	24.6	17.3	1	22.1	15.8	1	33.4	8.1	12
528	1	19.1	23.3	0			1	24.6	17.7	0			1	18.1	25.7	12
529	0			0			0			0			0			0
530	1	33.1	19.4	1	29.8	14.8	1	24.3	17.9	1	29.3	20.2	1	33.4	8.4	18
531	1	33.3	19.6	1	30	13.8	1	24.6	17.7	0			1	32.9	8.8	17
532	0			1	29.8	16	1	17.6	16.7	0			1	29.6	8.9	11
534	1	33.1	14.7	1	39.7	26.6	0			0			1	33.5	26.5	13
535	0			0			1	22	15.7	0			1	33.5	8.2	12
536	0			1	29.5	15.7	0			0			1	33.7	8.1	4
537	1	33.2	20.4	1	24.5	18.1	1	16.7	12.5	1	19.4	22.8	1	2.4	9.7	20
538	1	19.9	12.2	0			1	23.2	17.8	0			1	16.6	18.2	12
539	0			1	5.9	15.9	1	4.9	20.6	0			1	32.5	26.7	9
540	0			0			0			1	30.6	20.3	1	33	8.3	15
541	1	21.8	10.5	1	33.5	14.2	0			1	13.7	26.5	1	22.6	9.4	15
542	1	33.4	20.4	0			1	24.6	17.6	1	29.9	19.9	1	33	8.4	9
543	0			1	18.5	13.5	0			0			1	32.6	8.1	11
544	0			0			0			0			0			4
545	0			1	23.2	21.9	1	16.2	21.5	0			1	19.6	14.7	17

Figure 138: Spatial Cognition Study: First Series Landmark Placement Results (Page 1 of 2)

	Offset																			Offset	Offset	Offset
Subject	1	3	4	5	7	8	10	12	15	17	19	20	21	22	23	24	26	28	30	Total	Maximum	Average
Key	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
500	4.44	3.13	5.30	0.00	0.00	0.61	0.00	0.00	0.00	0.40	0.00	0.00	0.00	6.95	0.00	0.00	9.15	0.00	0.00	29.982	9.148	4.283
501	6.48	6.93	0.00	0.00	0.00	0.00	7.86	0.00	0.00	5.70	0.00	10.04	12.16	9.39	0.00	17.32	1.04	0.00	1.14	78.066	17.322	7.097
502	1.68	2.70	0.00	0.00	0.00	0.51	0.00	0.00	0.72	0.73	0.95	0.00	0.00	0.22	0.00	1.22	0.00	0.00	1.21	9.934	2.702	1.104
503	2.81	2.00	0.00	0.92	3.40	17.14	0.00	10.06	0.00	0.95	0.00	0.00	12.71	0.32	8.10	3.18	1.04	0.00	0.00	62.631	17.140	4.818
504	14.74	25.58	15.18	25.04	6.65	0.00	0.00	15.42	6.72	0.00	0.00	12.44	0.00	21.98	0.00	23.68	0.00	0.00	0.00	167.433	25.581	16.743
505	10.72	3.21	0.00	4.28	0.00	0.00	0.41	4.49	12.56	0.73	3.28	0.00	3.40	1.52	6.50	0.00	0.00	5.53	6.84	63.475	12.564	4.883
506	3.95	2.43	3.11	1.60	0.20	2.12	0.00	0.45	1.48	3.80	7.53	0.00	0.00	1.08	0.61	6.00	1.08	0.00	1.10	36.528	7.533	2.283
508	1.24	1.30	7.41	0.00	0.00	0.61	0.82	0.63	0.00	1.46	0.00	0.00	2.42	0.45	0.00	1.63	0.20	0.00	0.76	18.924	7.406	1.456
509	4.10	2.77	0.00	0.00	0.00	0.57	0.00	0.00	1.40	0.00	0.14	0.00	0.00	2.61	0.00	4.60	0.72	0.00	0.80	17.707	4.604	1.967
510	9.75	22.85	0.00	1.63	9.92	9.71	10.34	10.22	3.72	4.38	21.22	17.17	0.00	23.08	14.36	0.00	4.83	19.23	15.09	197.494	23.078	11.617
511	7.53	0.00	12.44	0.00	0.00	9.60	0.00	12.71	7.39	0.00	14.38	11.72	20.30	7.63	0.00	0.61	0.00	0.00	3.67	107.983	20.300	9.817
512	1.36	11.40	0.00	0.00	3.67	2.88	0.00	0.00	6.58	12.06	0.00	0.00	0.00	12.14	5.71	14.31	5.91	0.00	0.86	76.883	14.314	6.407
513	5.11	7.53	1.93	3.55	7.03	0.00	0.00	0.00	3.58	0.00	2.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	28.82	60.153	28.821	6.684
514	23.88	20.80	19.14	0.00	21.53	0.00	0.00	16.22	0.00	14.53	0.00	0.86	0.00	12.11	0.00	1.62	0.00	0.00	0.00	130.700	23.883	14.522
515	6.50	3.11	0.00	2.22	7.41	4.89	0.00	0.72	4.97	0.82	0.00	0.00	0.28	1.58	0.00	3.21	1.22	1.60	0.72	39.247	7.406	2.803
516	6.45	18.59	13.69	0.64	0.00	4.08	0.00	15.61	3.67	12.48	0.00	0.00	14.80	20.50	15.87	21.54	14.14	0.73	3.21	166.004	21.542	10.375
517	5.00	1.66	1.43	0.00	0.00	0.00	0.00	13.85	6.93	13.24	0.00	0.00	0.00	2.12	0.00	3.77	0.00	0.00	0.94	48.935	13.846	4.893
518	12.11	12.50	12.21	0.00	0.00	22.57	28.77	0.00	8.92	0.00	0.00	0.00	0.00	11.90	14.81	4.83	20.65	0.00	17.83	167.090	28.768	13.924
520	8.50	3.20	0.00	0.30	0.00	0.58	0.00	0.00	0.00	12.40	0.00	0.00	0.10	0.54	0.00	1.80	0.00	0.00	0.78	28.205	12.398	2.820
521	0.63	7.10	0.00	0.00	1.44	0.22	0.00	0.45	4.41	2.04	0.54	0.00	0.22	0.30	0.00	2.10	0.58	0.00	0.82	20.868	7.101	1.491
522	13.91	15.20	0.00	0.00	15.21	0.00	5.46	0.00	23.18	0.00	22.34	19.73	0.00	18.68	0.00	19.24	0.00	0.00	21.92	174.875	23.181	15.898
523	2.20	2.52	1.40	0.00	0.67	0.00	0.51	0.36	0.00	0.00	0.00	0.00	0.00	0.10	0.20	2.20	1.36	0.00	0.90	12.423	2.518	1.129
524	0.78	2.19	0.00	0.00	4.66	4.83	8.45	0.00	3.45	3.51	0.00	0.00	1.12	2.11	0.00	3.10	0.00	0.00	3.01	37.210	8.450	3.101
525	5.91	3.44	4.24	0.00	2.11	2.47	0.00	0.00	5.78	0.32	2.36	0.00	0.00	1.90	17.95	0.32	0.00	0.00	1.00	47.788	17.947	3.982
526	1.49	0.73	0.00	0.22	0.00	0.00	0.00	7.93	5.10	0.22	0.00	3.71	0.00	4.91	0.00	1.51	0.00	0.00	0.28	26.107	7.931	2.611
527	1.32	2.60	0.00	0.41	3.00	0.20	0.00	0.00	1.84	3.01	0.00	0.00	0.00	4.43	4.51	0.00	0.58	9.04	1.36	32.305	9.043	2.692
528	7.35	13.82	4.97	0.00	0.00	5.05	0.00	2.52	15.73	6.43	0.00	0.00	0.00	8.00	14.46	0.00	0.32	0.00	22.08	100.733	22.084	8.394
529	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	#DIV/0!
530	1.22	2.60	2.45	0.57	1.43	0.14	0.30	0.00	1.08	0.40	0.30	0.00	0.50	1.39	0.71	1.50	0.10	0.70	1.08	16.466	2.602	0.915
531	0.63	1.12	0.60	2.14	0.00	0.28	0.54	0.41	0.32	1.94	0.50	0.30	0.60	0.42	0.51	0.51	0.32	0.00	0.61	11.748	2.138	0.691
532	6.74	1.24	4.40	4.88	0.00	17.86	0.00	0.22	0.00	0.00	0.00	13.58	0.00	0.00	0.00	2.70	6.79	0.00	3.44	61.863	17.864	5.624
534	28.81	13.75	13.02	25.93	0.00	22.36	36.88	0.00	0.00	27.20	3.30	0.00	0.00	10.10	5.40	16.52	0.00	0.00	17.11	220.393	36.885	16.953
535	8.29	5.59	0.00	2.12	0.00	7.22	7.41	0.00	3.72	5.48	0.00	2.82	0.22	2.55	0.00	0.00	3.11	0.00	1.30	49.846	8.287	4.154
536	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33	0.00	0.22	0.00	2.43	0.00	0.00	1.48	5.467	2.433	1.367
537	8.47	18.65	21.82	15.96	20.82	15.78	11.68	11.84	6.91	23.56	4.33	27.69	3.14	28.46	0.30	7.22	9.27	10.91	30.60	277.418	30.601	13.871
538	12.71	10.47	9.34	0.00	0.00	4.32	13.82	0.00	10.50	2.06	0.00	0.00	0.00	7.71	15.47	0.00	1.10	0.00	18.61	106.112	18.612	8.843
539	13.54	20.58	0.00	0.00	16.23	0.00	0.00	0.00	0.00	12.51	0.00	25.78	0.00	25.48	0.00	24.14	19.60	0.00	17.31	175.167	25.775	19.463
540	1.80	5.38	1.63	0.45	3.97	0.28	0.00	12.73	5.50	1.10	0.63	0.00	12.62	0.00	0.00	0.00	0.00	0.61	1.10	47.803	12.732	3.187
541	4.61	11.67	12.13	5.65	4.58	0.00	0.00	0.00	25.05	6.12	0.00	12.84	26.84	0.64	14.90	3.71	0.00	17.48	10.40	156.616	26.837	10.441
542	4.10	0.00	0.00	0.00	0.00	1.03	0.00	0.63	0.00	2.72	0.00	0.00	0.00	0.28	0.36	0.00	0.36	0.32	1.00	10.804	4.105	1.200
543	14.74	19.60	8.10	0.00	9.30	0.00	15.43	0.00	0.00	11.79	0.00	9.09	0.00	25.90	0.00	11.40	0.00	0.00	1.36	126.705	25.902	11.519
544	23.60	9.93	0.00	0.00	0.00	8.45	0.00	0.00	16.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	58.690	23.602	14.673
545	3.51	3.73	15.52	1.96	3.86	4.39	3.82	4.16	4.53	5.31	2.59	22.55	0.00	9.45	0.00	10.90	8.91	0.00	14.41	119.626	22.550	7.037

Figure 139: Spatial Cognition Study: First Series Landmark Placement Results (Page 2 of 2)

Subject	Group	S Total	MV Total	Average Landmark Offset Error (50th's of an inch)	Recognition Errors (out of 30)
801	control	78.14	90.28	3.247	9
802	top-down	76.26	44.44	3.761	8
803	top-down (tracked)	44.79	43.4	5.296	16
804	top-down (tracked)	46.73	52.78	1.501	4
805	control	25.83	77.08	17.208	5
806	control	58.42	52.78	1.786	6
807	top-down	38.53	50.69	9.181	8
808	control	29.06	52.78	7.524	5
809	control	32.28	59.03	1.683	1
810	perspective	34.09	72.92	2.995	6
811	control	20.55	64.58	2.344	4
812	top-down	62.05	5.9	7.459	8
813	top-down (tracked)	39.52	70.14	1.04	2
814	control	45.97	59.38	2.879	2
815	perspective	40.3	51.39	1.904	3
816	perspective	63.45	57.64	1.55	8
817	control	46.4	57.29	3.757	5
818	top-down (tracked)	35.67	36.11	4.303	2
819	top-down (tracked)	32.63	36.81	5.432	5
820	control	50.61	47.22	10.551	6
821	top-down	29.38	14.58	10.57	2
822	top-down	36.26	70.83	0.997	3
823	control	65.58	74.31	1.102	0
824	top-down (tracked)	61.34	52.08	4.159	5
825	control	34.78	44.44	1.087	1
826	top-down	41.53	79.51	4.012	5
827	top-down	44.73	5.56	6.03	7
828	control	11.37	53.47	2.213	5
829	top-down (tracked)	31.21	-24.31	8.17	8
830	control	26.09	49.31	1.786	7
831	top-down (tracked)	32.01	84.72	7.031	12
832	control	29.23	53.13	2.841	7
833	control	54.38	66.67	1.401	8
834	top-down	49.12	61.81	4.356	10
835	top-down	15.4	52.08	11.24	3
836	control	56.5	50	1.003	0
837	top-down	74.96	97.22	2.687	5
838	top-down	46.79	60.42	21.138	5
839	control	48.81	66.67	5.397	8
840	top-down	-5.71	43.06	2.453	5
841	control	52.47	25	13.288	6
842	top-down	38.17	58.33	1.496	1
843	top-down	29.76	66.67	5.005	7
844	control (tracked)	17.75	62.5	3.958	4

Figure 140: Spatial Cognition Study: Second Series, Phase 1 Data Summary

Second Series Spatial Rotation Scores
Phase 1
from: EKSTROM, R., FRENCH, J., HARMAN, H., and DERMEN, D., Manual for Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service, NR 150 329, 1976.

Participant	S1 (Part 1, 160 questions, 2D rotations)				S2 (Part 2, 42 questions, 3D rotations)				S Total
Number	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	%
801	153	1	151	94.38	42	8	26	61.90	78.14
802	155	5	145	90.63	42	8	26	61.90	76.26
803	104	7	90	56.25	40	13	14	33.33	44.79
804	128	14	100	62.50	29	8	13	30.95	46.73
805	70	7	56	35.00	33	13	7	16.67	25.83
806	148	11	126	78.75	42	13	16	38.10	58.42
807	109	10	89	55.63	29	10	9	21.43	38.53
808	105	6	93	58.13	30	15	0	0.00	29.06
809	71	1	69	43.13	15	3	9	21.43	32.28
810	89	9	71	44.38	38	14	10	23.81	34.09
811	127	23	81	50.63	42	23	-4	-9.52	20.55
812	152	11	130	81.25	42	12	18	42.86	62.05
813	108	6	96	60.00	26	9	8	19.05	39.52
814	125	8	109	68.13	26	8	10	23.81	45.97
815	72	2	68	42.50	26	5	16	38.10	40.30
816	104	0	104	65.00	28	1	26	61.90	63.45
817	158	20	118	73.75	42	17	8	19.05	46.40
818	61	2	57	35.63	29	7	15	35.71	35.67
819	139	23	93	58.13	23	10	3	7.14	32.63
820	129	14	101	63.13	42	13	16	38.10	50.61
821	154	30	94	58.75	42	21	0	0.00	29.38
822	115	9	97	60.63	39	17	5	11.90	36.26
823	113	3	107	66.88	41	7	27	64.29	65.58
824	120	19	82	51.25	42	6	30	71.43	61.34
825	85	4	77	48.13	27	9	9	21.43	34.78
826	91	0	91	56.88	13	1	11	26.19	41.53
827	100	7	86	53.75	29	7	15	35.71	44.73
828	122	39	44	27.50	36	19	-2	-4.76	11.37
829	99	11	77	48.13	40	17	6	14.29	31.21
830	59	3	53	33.13	18	5	8	19.05	26.09
831	91	0	91	56.88	35	16	3	7.14	32.01
832	54	5	44	27.50	23	5	13	30.95	29.23
833	104	5	94	58.75	37	8	21	50.00	54.38
834	105	12	81	50.63	42	11	20	47.62	49.12
835	41	13	15	9.38	31	11	9	21.43	15.40
836	105	4	97	60.63	26	2	22	52.38	56.50
837	143	3	137	85.63	33	3	27	64.29	74.96
838	104	0	104	65.00	16	2	12	28.57	46.79
839	94	7	80	50.00	42	11	20	47.62	48.81
840	118	51	16	10.00	21	15	-9	-21.43	-5.71
841	128	1	126	78.75	33	11	11	26.19	52.47
842	93	14	65	40.63	37	11	15	35.71	38.17
843	62	31	0	0.00	29	2	25	59.52	29.76
844	57	2	53	33.13	19	9	1	2.38	17.75

Figure 141: Spatial Cognition Study: Second Series, Phase 1 Spatial Rotation Test Results

Second Series Visual Memory Scores
Phase 1
from: EKSTROM, R., FRENCH, J., HARMAN, H., and DERMEN, D., Manual for Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service, NR 150 329, 1976.

Participant	MV1 (Part 1, 32 questions, Shape Memory)				MV2 (Part 2, 24 questions, Building Memory)				MV3 (Part 3, 24 questions, Map Memory)				MV Total
Number	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	%
801	32	2	28	87.50	24	0	24	100.00	22	0	20	83.33	90.28
802	32	4	24	75.00	11	0	-2	-8.33	20	0	16	66.67	44.44
803	25	5	15	46.88	18	3	3	12.50	23	3	17	70.83	43.40
804	32	4	24	75.00	15	0	6	25.00	19	0	14	58.33	52.78
805	32	7	18	56.25	22	0	20	83.33	23	0	22	91.67	77.08
806	32	4	24	75.00	15	0	6	25.00	19	0	14	58.33	52.78
807	32	9	14	43.75	18	2	6	25.00	22	0	20	83.33	50.69
808	32	4	24	75.00	18	0	12	50.00	16	0	8	33.33	52.78
809	32	7	18	56.25	15	1	5	20.83	24	0	24	100.00	59.03
810	32	3	26	81.25	20	0	15	62.50	21	0	18	75.00	72.92
811	30	4	22	68.75	17	0	9	37.50	23	0	21	87.50	64.58
812	31	10	11	34.38	8	0	-8	-33.33	14	0	4	16.67	5.90
813	32	5	22	68.75	20	0	16	66.67	21	0	18	75.00	70.14
814	31	5	21	65.63	18	0	12	50.00	21	3	15	62.50	59.38
815	32	6	20	62.50	14	0	4	16.67	21	0	18	75.00	51.39
816	32	5	22	68.75	15	0	6	25.00	22	0	19	79.17	57.64
817	31	0	31	96.88	13	0	2	8.33	22	0	16	66.67	57.29
818	32	6	20	62.50	13	0	2	8.33	23	7	9	37.50	36.11
819	32	9	14	43.75	14	2	0	0.00	20	0	16	66.67	36.81
820	32	4	24	75.00	14	0	4	16.67	18	0	12	50.00	47.22
821	32	11	10	31.25	11	0	-3	-12.50	15	0	6	25.00	14.58
822	32	4	24	75.00	18	0	12	50.00	23	0	21	87.50	70.83
823	32	5	22	68.75	19	0	14	58.33	24	1	23	95.83	74.31
824	32	9	14	43.75	17	0	10	41.67	21	0	17	70.83	52.08
825	32	0	32	100.00	11	0	-2	-8.33	17	0	10	41.67	44.44
826	31	4	23	71.88	21	0	18	75.00	23	0	22	91.67	79.51
827	32	10	12	37.50	8	1	-11	-45.83	15	0	6	25.00	5.56
828	32	5	22	68.75	15	0	6	25.00	20	0	16	66.67	53.47
829	32	21	-10	-31.25	4	0	-16	-66.67	15	0	6	25.00	-24.31
830	32	9	14	43.75	22	3	13	54.17	18	0	12	50.00	49.31
831	32	2	28	87.50	22	0	20	83.33	22	0	20	83.33	84.72
832	31	6	19	59.38	16	0	8	33.33	20	0	16	66.67	53.13
833	32	4	24	75.00	16	0	8	33.33	23	0	22	91.67	66.67
834	32	5	22	68.75	20	0	16	66.67	18	0	12	50.00	61.81
835	32	7	18	56.25	14	0	4	16.67	22	0	20	83.33	52.08
836	32	12	8	25.00	18	0	12	50.00	21	0	18	75.00	50.00
837	32	0	32	100.00	24	0	24	100.00	23	0	22	91.67	97.22
838	32	9	14	43.75	20	0	16	66.67	21	0	17	70.83	60.42
839	32	4	24	75.00	18	0	12	50.00	21	0	18	75.00	66.67
840	32	8	16	50.00	14	1	3	12.50	20	0	16	66.67	43.06
841	32	16	0	0.00	19	0	14	58.33	14	0	4	16.67	25.00
842	32	6	20	62.50	18	2	9	37.50	21	0	18	75.00	58.33
843	32	4	24	75.00	19	0	14	58.33	20	0	16	66.67	66.67
844	32	2	28	87.50	19	0	14	58.33	17	0	10	41.67	62.50

Figure 142: Spatial Cognition Study: Second Series, Phase 1 Visual Memory Test Results

Subject	1			3			4			5		
	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	21.3	21.7	1	27.9	17.7	1	30	20.2	1	25.4	21.7
801	1	22.7	21.8	1	25.8	18	1	29.7	19	1	25.5	21.8
802	1	22.5	21.9	1	24.4	18.3	1	29.9	14.3	0		
803	1	23.2	14.6	1	26.5	21.2	0			0		
804	1	22.8	22.1	1	25.5	17.9	1	29.8	20.1	1	25.4	23.5
805	1	12.5	11.4	1	7.3	18.3	1	4.8	15.3	0		
806	1	23.4	21.7	1	26.2	17.9	1	29.7	22	1	25.5	22.1
807	1	11	8.8	1	21.2	18.1	1	11	2.1	0		
808	1	21.1	18.7	1	25.7	18.8	1	13.6	26.5	0		
809	1	24.1	21.6	1	29.2	17.1	1	29.6	21.7	1	25.3	21.9
810	1	29.8	17.6	1	26.1	17.7	1	29.8	15.1	1	18.8	21.1
811	1	24.2	21.7	1	25.3	18.5	1	29.8	21.5	1	25.9	22.7
812	1	25.4	26.6	1	22.6	10.2	1	29.5	13.2	1	25.6	25.5
813	1	22.4	21.7	1	27.8	17.8	1	29.7	19.1	1	25.6	22.3
814	1	27.1	21.2	1	26.8	18.1	1	28.8	19.2	1	25.6	22.4
815	1	24.2	22.4	1	24.9	17.1	0			0		
816	1	21.2	22.1	1	29.2	17.5	1	30.3	20	1	25.1	22.3
817	1	22	21.8	1	28.2	13.6	1	30	19.4	0		
818	1	22.7	21.8	1	25.5	17.9	1	33.4	19.9	0		
819	1	33.3	8.1	1	29	17.8	1	33.5	19.6	0		
820	1	40.1	22.2	1	29.2	13.8	1	29.6	11.2	0		
821	1	27.8	23.8	1	43.2	11.7	1	36.7	20.8	0		
822	1	22.5	22	1	27.1	18	1	29.8	20.4	0		
823	1	23.1	22	1	27	16.7	1	29.8	16	1	25.8	22.4
824	1	19.3	23.2	1	24.1	17.7	0			0		
825	1	21.8	21.8	1	28.8	17.9	1	29.9	17	0		
826	1	21.1	21.7	1	29	17.7	1	29.7	16.1	0		
827	1	25.2	23.5	1	25.2	16.8	1	25.7	22.5	0		
828	1	21.2	21.6	1	26.7	18	0			0		
829	1	33.1	20.7	1	28.3	8.8	1	33.1	14.5	1	22.7	9.2
830	1	22.8	22.3	1	27.6	17.9	1	29.6	18.1	0		
831	1	28.5	21.3	1	24.4	18.1	0			1	25.6	22.2
832	1	22.2	21.9	1	24.7	18.1	0			0		
833	1	22.3	21.6	1	24.9	17.3	0			0		
834	1	22.3	21.7	1	27.5	17.9	0			0		
835	1	25.4	23.6	1	6.9	13	1	31	27.5	1	29.8	22.6
836	1	22	21.8	1	26.9	18	1	29.1	21.5	1	25.4	22.3
837	1	22.3	21.9	1	27.4	17.9	0			0		
838	1	-0.4	13.2	1	2.5	18.9	1	-0.8	19.6	1	21	10.4
839	1	25.2	25.9	1	24.7	18.2	1	29.5	18.7	0		
840	1	22.1	22.2	1	24	18.1	0			1	25.4	22.5
841	0			1	5.4	20.1	1	5.5	15	1	25.2	22.8
842	1	22.7	21.8	1	26.7	17.6	1	29.9	14.9	1	25.9	23.8
843	1	28.1	21.6	1	24.5	18.5	0			0		
844	1	22.2	21.7	1	29.1	16.3	1	29.8	21.7	1	25.3	23.3

Subject	7			8			10			12			15		
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	24.9	17.9	1	17.9	15.9	1	14.3	20.7	1	29.1	21.8	1	33.1	16.3
801	1	26.4	20.7	0			0			1	33.6	17.2	1	33.4	13.8
802	1	28.6	21.1	1	17.2	17	1	15.7	21	0			1	37	11.2
803	0			0			0			0			0		
804	1	26.3	18.9	1	17.5	16.5	1	14.8	21.1	1	29.4	21.4	1	33.3	14.8
805	0			1	5	21.6	1	9.6	8.7	1	12.8	21.3	1	12.3	5.5
806	0			1	19	14.5	1	18.2	21	1	29.8	20	1	33.4	12.7
807	1	9.1	8	1	15.2	16.7	0			1	9.3	13.5	1	38.8	12.9
808	1	28.8	19	1	15.1	16.3	0			1	14.8	26.5	1	25.7	21.9
809	1	26.5	20.9	1	17.3	16.6	1	19.5	21	1	29.6	21.7	1	33.2	17.9
810	0			1	16.3	17.5	0			1	29.7	22	1	33.5	20.8
811	0			1	17.6	15.6	1	15.5	21.1	1	22	16	1	29.9	14.9
812	0			1	14.8	19.7	1	17.2	21.2	1	17.6	15.5	1	29.6	10.5
813	1	25.5	17.9	1	18.4	14.7	1	14.7	21	1	29.7	21.6	1	33.4	14.7
814	1	24.5	21.8	1	17.4	16.5	1	14.6	21.1	1	33	16.2	1	33.4	15.2
815	1	29.9	17	1	17.4	17.2	1	15.1	21	1	29.2	22.2	1	32.9	15.5
816	0			1	17.7	16.8	0			0			1	33.2	20.7
817	1	23.9	13.1	1	17.9	15.7	1	14.2	21.1	1	34.3	20.7	1	33.4	13.7
818	1	31.2	14.5	1	18	15.2	1	17	20.9	1	40.2	19.9	1	40.1	11.8
819	1	20.1	21.1	1	29.6	8.8	1	14.8	21.1	1	33.5	15.7	1	22.9	21.2
820	0			1	28.8	21.2	1	33.4	25.5	0			0		
821	1	27.4	20.7	1	42.3	6	1	40.2	9.3	1	39.1	21	1	37.2	17
822	1	27.3	20.7	1	17.5	16.7	1	14.7	20.9	1	29.5	17.6	1	33.4	15.2
823	1	25.7	16.8	1	17.7	15.9	1	15.5	20.1	1	29.2	21.5	1	33.4	14.5
824	1	25	23.3	1	17.4	16.7	1	17.2	21.1	1	25	22.2	1	25.1	19.8
825	1	25.4	18.7	1	17.2	17.1	1	15.2	20.8	1	29.3	22.2	1	33.1	15.2
826	1	25.3	18.2	1	17.4	16.3	1	29.6	8.9	1	23.2	22	1	32.8	15.6
827	1	28.3	21.3	0			1	24.6	11.8	1	23.5	21.7	0		
828	1	33.2	21	1	17.6	16.6	1	14.5	21.1	1	33.1	13.1	0		
829	0			1	19.9	12.6	0			1	18.2	14.4	0		
830	1	26	20.4	1	15.3	17.6	1	16.4	21.1	1	28.8	17.8	1	33.1	14.7
831	1	24.7	21.9	1	16.2	16.1	1	18.7	21.8	0			1	39.3	13.2
832	0			1	17.5	17	1	18.5	21.1	1	28.8	21.7	1	34.1	15.1
833	0			1	17.7	15.5	1	16.4	20.6	0			1	33.1	17.3
834	0			1	15	16.8	1	21.7	18.7	1	29.4	8.5	0		
835	0			1	17.5	18	1	25.5	16.1	1	34	27.6	1	-0.6	13
836	1	26.7	19.2	1	17.4	15.6	1	13.2	21.2	1	29.5	19.5	1	33.3	15.7
837	0			1	17.6	16.2	1	19	21.3	1	33.2	18	1	33.2	16.6
838	1	6.2	14.5	1	15.3	20.7	0			1	-0.7	16.4	1	11.3	25.3
839	0			1	16.4	18.7	1	11.9	15.7	1	29.4	17	0		
840	0			1	17.5	16	1	22.2	16.2	1	29.2	22	1	32.9	12.5
841	0			1	15.2	17.5	0			1	24.9	16.8	1	36.3	14.4
842	1	28	18.6	1	18.2	15.9	1	17.8	21.1	1	29.7	18.8	1	33.5	16.4
843	0			1	14.1	17.1	1	15	21.7	1	24.4	16.7	1	37.1	15
844	1	26.3	19.5	1	21.5	18.1	1	19.2	20.6	1	28.5	21.4	1	20.5	18.7

Subject	16			17			19			20			21		
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	14.3	20.7	1	21.7	16.2	1	33.2	20.1	1	33.1	11.8	1	30.1	8.9
801	0			1	16	20.9	0			0			0		
802	0			1	20.8	18.1	1	34.3	10.4	1	23.5	14.2	1	28.9	8.8
803	1	41.6	18.2	0			0			0			0		
804	1	13.9	21.2	1	19.2	15.4	1	33.1	20.3	1	33.4	12.5	1	29.7	2.9
805	1	5.1	5.5	0			1	9.5	23	1	15.9	2.1	0		
806	0			1	22.3	15.7	1	33.4	16	0			0		
807	0			1	18.3	16.3	0			0			0		
808	0			1	20.3	15.7	1	21.2	22.2	1	17.7	21	1	29.3	9.1
809	1	14.7	20.3	1	24.6	16.1	1	33.2	20.9	1	33.2	15.3	0		
810	1	13.7	22	0			1	29.8	19.5	1	33.5	14.5	0		
811	0			1	19.7	16	1	29.9	19.5	0			0		
812	0			0			1	29.8	19.1	1	22	21.1	0		
813	0			1	22.3	15.8	1	33.3	16.9	0			1	29.9	8.8
814	1	18.3	15.6	1	21.7	16	1	40.2	17.7	0			0		
815	1	15.1	19.9	1	21.7	15.9	0			0			1	30	15.5
816	0			1	24.9	16.1	1	33.1	19.6	0			0		
817	0			1	19	12.8	1	33.6	10.3	0			1	33.3	7.7
818	1	14	20.6	1	22	15.9	1	40.2	16.4	0			1	30.3	8.2
819	1	29.6	17.7	0			1	30.2	20.3	0			1	31.5	8.1
820	1	33.5	19.4	1	33.2	23.8	1	34.5	11	1	33.4	16	0		
821	1	36.7	20.8	1	37.7	7.6	1	41.4	20.8	0			1	40.1	16.6
822	0			1	21.6	16.3	1	33.5	20.3	1	33.4	12	1	30.1	8.9
823	1	15	20.4	1	21.4	16	1	33.1	20.1	1	33.4	16.2	1	29.7	8.6
824	1	14.7	20.3	1	21.7	15.9	1	25.1	20.6	0			0		
825	1	15.1	20	1	20.1	16.2	1	33.1	19.5	1	33.1	10.9	1	30.4	9.3
826	0			1	16.7	21.3	1	33.1	10.4	0			0		
827	0			1	22.3	18.2	0			0			0		
828	0			1	24.7	17.2	1	33	19.3	1	33.2	17.4	1	29.9	8.8
829	1	33.4	17.5	0			0			0			1	29.6	26.5
830	0			1	22.2	15.8	1	33.8	19.9	0			0		
831	0			0			1	9.6	23.5	0			0		
832	0			0			1	35.9	20.7	0			1	22.7	8.9
833	1	14	20.7	1	20.1	16.2	0			0			0		
834	0			1	17.3	17.2	0			0			0		
835	1	18.4	26.7	1	17.9	14.9	1	27.1	26.7	1	28.3	18	0		
836	1	12.6	22.1	1	23	15.9	1	32.2	21	1	33.2	12.2	1	29.6	8.8
837	1	14	20.7	1	16.7	21.1	0			1	33.5	12.8	1	29.3	8.6
838	1	18.9	13.7	1	9.3	8	0			0			0		
839	1	10.9	24.7	0			1	33	18.8	1	26	8.8	0		
840	0			1	19.7	16.1	1	29.5	18.5	1	29.6	10.5	0		
841	1	20.3	18	0			1	22	22.2	1	13.1	21.2	0		
842	0			1	22.3	15.8	1	32.6	20.7	1	34.5	13	1	30.4	8.9
843	1	9.9	23.6	1	22.3	10.4	0			0			1	33.2	7.9
844	1	21.3	21	1	20.7	20	1	28.9	19.3	1	28.7	16.7	1	28.5	18

Subject	22			23			24			26			28			30			Total
	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y	
Key	1	29.9	17.5	1	33.2	20.1	1	29.9	13.3	1	24.3	17.8	1	30	20.2	1	33	9.4	20
801	1	29.7	17.3	0			1	17.7	15.8	1	24.6	17.2	0			1	33.3	8.3	12
802	1	25.6	19	1	33.3	18.3	0			1	20.7	20.2	1	30.7	19.8	1	33.1	8.4	16
803	0			1	25.5	18.6	0			0			0			1	40.4	8.1	5
804	1	30	17.4	1	33.2	19.1	1	33.7	10.2	1	24.5	17.1	0			1	33.3	8.4	19
805	1	18.5	14.3	1	29.7	2.7	1	9.3	18.4	1	4.7	17.5	1	6.3	13.3	1	26	16.6	16
806	1	29.6	17.5	1	33.4	19.9	1	29.7	11.4	1	24.6	16.9	0			1	33.4	8.3	15
807	1	28.7	17.9	0			1	29.9	12.1	1	23.2	17.9	0			1	28.9	8.6	12
808	1	28.8	16.8	1	14.1	20.8	1	29.6	13.9	1	27.8	14.1	0			0			15
809	1	29.8	17.5	1	33.1	20	1	29.8	15.4	1	25.3	16.4	1	29.9	22.8	1	33.2	9.8	19
810	1	29.8	16.6	1	33.5	18.2	0			1	24.5	16.3	0			1	33.5	8.5	14
811	1	29.4	17.6	1	33.6	16.7	1	29.9	16.3	1	24.7	16.5	1	29.9	20.3	1	33.5	8.2	16
812	0			0			1	16.3	17.7	0			1	24.9	21.3	1	27.7	9.4	13
813	1	29.9	15.9	1	33.4	18.8	1	29.8	12.4	1	25.3	16.7	1	30.5	20.8	1	33.4	8.7	18
814	1	30	17.4	0			1	29.7	15.2	0			1	36.4	17	1	39.8	9	16
815	1	29.9	17	1	33	19.4	1	30	15.5	1	26.6	15.6	1	31.6	20.8	1	33.2	8.8	16
816	1	30.2	16.9	1	33	18	0			1	24.6	17.7	0			1	29.3	9.6	12
817	1	29.8	13.4	1	32.6	11.6	1	32.9	14.6	1	21.5	12.9	0			1	34.1	7.8	16
818	1	29.7	16.5	1	40.2	14.6	1	33.5	11.6	1	24.8	16.7	1	15.9	18.7	1	33.6	7.8	18
819	1	26.4	16.6	1	33.6	13.4	1	29.9	16.5	1	20.3	16.1	0			1	33.7	6.8	16
820	1	40	8.5	1	40.5	5.9	1	34.2	7.9	1	40.3	17.1	0			1	28.8	8.2	14
821	1	42	14.7	1	40.5	15.2	1	29.8	18.2	1	40	11.6	1	33.6	21.1	1	34	7.7	18
822	1	30	17.4	0			1	29.9	11.2	1	24.5	17.6	1	30.4	19.9	1	33	9.1	17
823	1	29.8	17.3	1	33.1	19.5	1	29.8	13.7	1	24.3	17.4	1	29.8	20	1	33.6	8	20
824	1	24.9	16.2	1	23.7	18.6	0			1	23.6	16.1	1	25.1	18.8	1	29.2	9	15
825	1	29.4	16.6	1	33.1	17.3	1	30.2	15.6	1	24.7	17.6	1	30.2	20.2	1	33.2	8.6	19
826	1	29.9	17.2	1	33	19.7	1	29.9	12.4	1	24.1	17.6	1	17.5	17.7	1	33.1	9.5	16
827	1	26.3	16.4	0			1	25.5	25.6	1	25.9	17.7	0			1	29.7	18.6	11
828	1	29.9	17.3	1	33.2	20.4	1	30	11.8	1	24.5	16.6	1	30.4	20.8	1	33.2	8.8	16
829	1	33.3	23.4	1	33.3	25.8	0			1	26.3	26.6	0			1	31.7	8.1	12
830	1	28.8	17.8	1	32.8	18.3	1	29.5	15.4	0			1	30.1	21.1	0			14
831	1	29	17.4	0			0			0			0			1	33	26.5	10
832	1	29	17.6	1	33.2	17.6	1	20.8	12.6	1	23.8	16	0			1	33.3	8.5	13
833	1	29	17.1	1	33.2	15.9	0			1	24.1	16.5	1	29.9	20	1	32.9	8.5	12
834	1	29.6	16.8	0			1	33.2	15.5	1	20.3	18.2	0			1	28.2	8.7	10
835	1	7.1	15.7	0			1	22.8	26.7	1	29	17	1	11.9	26.6	1	18.9	13.3	17
836	1	29.5	19.5	1	33.2	21	1	29.6	14.2	1	24.4	17.3	1	29.6	20.4	1	33.1	8.7	20
837	1	29.4	13	1	33.2	19.5	1	29.6	10.6	0			1	20.5	20.5	1	32.9	8	15
838	1	13.1	9.6	0			1	5.5	9.8	1	11.2	8.5	1	-0.2	7.6	1	9.3	21.1	15
839	1	25.5	17.9	0			0			1	10.2	16.5	0			1	20.2	12.1	12
840	1	28.8	17.7	1	32.7	17.9	1	29.6	16.7	0			1	29.9	20	1	32.8	8.6	15
841	1	8.9	14.9	1	11.3	23.6	1	9.3	18	1	17.6	19.2	1	25.1	25.4	1	14.6	26.6	15
842	1	29.7	17.1	1	33	19	1	29.8	12.2	1	24.3	17.8	1	30.4	20	1	33.3	8.4	19
843	1	25.6	18.9	1	16.1	20.7	0			0			0			1	33	6.7	12
844	1	25.8	20.9	1	30.2	18.6	0			1	21.9	18.9	1	30.2	20.4	1	29.3	17.4	19

Figure 143: Spatial Cognition Study: Second Series, Phase 1 Landmark Placement Results (Page 1 of 2)

	3	4	5	7	8	10	12	15	17	19	20	21	22	23	24	26	28	30	Offset Total	Offset Maximum	Offset Average
Subject																					
Key	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
801	2.12	1.24	0.14	3.18	0.00	0.00	6.44	2.52	7.39	0.00	0.00	0.00	0.28	0.00	12.45	0.67	0.00	1.14	838.564	801.000	69.880
802	3.55	5.90	0.00	4.89	1.30	1.43	0.00	6.42	2.10	9.76	9.90	1.20	4.55	1.80	0.00	4.33	0.81	1.00	860.959	802.000	53.810
803	3.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.84	0.00	0.00	0.00	7.51	822.128	803.000	164.426
804	2.41	0.22	1.80	1.72	0.72	0.64	0.50	1.51	2.62	0.22	0.76	6.01	0.14	1.00	4.90	0.73	0.00	1.04	830.968	804.000	43.735
805	20.61	25.67	0.00	0.00	14.10	12.89	16.31	23.44	0.00	23.88	19.75	0.00	11.84	17.75	21.22	19.60	24.68	10.04	1066.779	805.000	66.674
806	1.71	1.82	0.41	0.00	1.78	3.91	1.93	3.61	0.78	4.10	0.00	0.00	0.30	0.28	1.91	0.95	0.00	1.17	830.683	806.000	55.379
807	6.71	26.24	0.00	18.65	2.82	0.00	21.47	6.64	3.40	0.00	0.00	0.00	1.26	0.00	1.20	1.10	0.00	4.18	900.669	807.000	75.056
808	2.46	17.57	0.00	4.05	2.83	0.00	15.05	9.28	1.49	12.18	17.94	0.82	1.30	19.11	0.67	5.09	0.00	0.00	917.854	808.000	61.190
809	1.43	1.55	0.22	3.40	0.92	5.21	0.51	1.60	2.90	0.80	3.50	0.00	0.10	0.14	2.10	1.72	2.60	0.45	838.168	809.000	44.114
810	1.80	5.10	6.63	0.00	2.26	0.00	0.63	4.52	0.00	3.45	2.73	0.00	0.91	1.92	0.00	1.51	0.00	1.03	842.498	810.000	60.178
811	2.72	1.32	1.12	0.00	0.42	1.26	9.17	3.49	2.01	3.35	0.00	0.00	0.51	3.42	3.00	1.36	0.14	1.30	845.603	811.000	52.850
812	9.18	7.02	3.81	0.00	4.90	2.94	13.11	6.77	0.00	3.54	14.48	0.00	0.00	0.00	14.29	0.00	5.22	5.30	902.577	812.000	69.429
813	0.14	1.14	0.63	0.60	1.30	0.50	0.63	1.63	0.72	3.20	0.00	0.22	1.60	1.32	0.91	1.49	0.78	0.81	830.615	813.000	46.145
814	1.17	1.56	0.73	3.92	0.78	0.50	6.82	1.14	0.20	7.40	0.00	0.00	0.14	0.00	1.91	0.00	7.16	6.81	854.246	814.000	53.390
815	3.06	0.00	0.00	5.08	1.39	0.85	0.41	0.82	0.30	0.00	0.00	6.60	0.50	0.73	2.20	3.18	1.71	0.63	842.479	815.000	52.655
816	1.32	0.36	0.67	0.00	0.92	0.00	0.00	4.40	3.20	0.51	0.00	0.00	0.67	2.11	0.00	0.32	0.00	3.71	834.183	816.000	69.515
817	4.11	0.80	0.00	4.90	0.20	0.41	5.32	2.62	4.34	9.81	0.00	3.42	4.10	8.52	3.27	5.64	0.00	1.94	876.403	817.000	54.775
818	2.41	3.41	0.00	7.16	0.71	2.71	11.26	8.32	0.42	7.92	0.00	0.73	1.02	8.90	3.98	1.21	14.18	1.71	894.048	818.000	49.669
819	1.10	3.55	0.00	5.77	13.69	0.64	7.52	11.32	0.00	3.01	0.00	1.61	3.61	6.71	3.20	4.35	0.00	2.69	887.772	819.000	55.486
820	4.11	9.01	0.00	0.00	12.12	19.69	0.00	0.00	13.78	9.19	4.21	0.00	13.53	15.97	6.90	16.02	0.00	4.37	948.902	820.000	67.779
821	16.43	6.73	0.00	3.75	26.33	28.30	10.03	4.16	18.16	8.23	0.00	12.62	12.42	8.79	4.90	16.88	3.71	1.97	1004.427	821.000	55.802
822	0.85	0.28	0.00	3.69	0.89	0.45	4.22	1.14	0.14	0.36	0.36	0.00	0.14	0.00	2.10	0.28	0.50	0.30	837.713	822.000	49.277
823	1.35	4.20	0.81	1.36	0.20	1.34	0.32	1.82	0.36	0.10	4.41	0.50	0.22	0.61	0.41	0.40	0.28	1.52	843.220	823.000	42.161
824	3.80	0.00	0.00	5.40	0.94	2.93	4.12	8.73	0.30	8.12	0.00	0.00	5.17	9.62	0.00	1.84	5.10	3.82	883.878	824.000	58.925
825	0.92	3.20	0.00	0.94	1.39	0.91	0.45	1.10	1.60	0.61	0.90	0.50	1.03	2.80	2.32	0.45	0.20	0.82	845.140	825.000	44.481
826	1.10	4.11	0.00	0.50	0.64	19.32	5.90	0.76	7.14	9.70	0.00	0.00	0.30	0.45	0.90	0.28	12.75	0.14	890.000	826.000	55.625
827	2.85	4.88	0.00	4.81	0.00	13.61	5.60	0.00	2.09	0.00	0.00	0.00	3.76	0.00	13.06	1.60	0.00	9.77	889.037	827.000	80.822
828	1.24	0.00	0.00	8.86	0.76	0.45	9.58	0.00	3.16	0.82	5.60	0.22	0.20	0.30	1.50	1.22	0.72	0.63	863.266	828.000	53.954
829	8.91	6.49	12.79	0.00	3.86	0.00	13.17	0.00	0.00	0.00	0.00	17.61	6.81	5.70	0.00	9.02	0.00	1.84	915.199	829.000	76.267
830	0.36	2.14	0.00	2.73	3.11	2.14	4.01	1.60	0.64	0.63	0.00	0.00	1.14	1.84	2.14	0.00	0.91	0.00	853.385	830.000	60.956
831	3.52	0.00	0.54	4.00	1.71	4.54	0.00	6.93	0.00	23.84	0.00	0.00	0.91	0.00	0.00	0.00	0.00	17.10	894.094	831.000	89.409
832	3.22	0.00	0.00	0.00	1.17	4.22	0.32	1.56	0.00	2.77	0.00	7.40	0.91	2.50	9.13	1.87	0.00	0.95	868.008	832.000	66.770
833	3.03	0.00	0.00	0.00	0.45	2.10	0.00	1.00	1.60	0.00	0.00	0.00	0.98	4.20	0.00	1.32	0.22	0.91	848.805	833.000	70.734
834	0.45	0.00	0.00	0.00	3.04	7.67	13.30	0.00	4.51	0.00	0.00	0.00	0.76	0.00	3.97	4.02	0.00	4.85	876.563	834.000	87.656
835	21.52	7.37	4.49	0.00	2.14	12.11	7.59	33.86	4.02	8.99	7.84	0.00	22.87	0.00	15.16	4.77	19.20	14.63	1021.554	835.000	60.091
836	1.04	1.58	0.60	2.22	0.58	1.21	2.33	0.63	1.33	1.35	0.41	0.51	2.04	0.90	0.95	0.51	0.45	0.71	855.358	836.000	42.768
837	0.54	0.00	0.00	0.00	0.42	4.74	5.59	0.32	7.00	0.00	1.08	0.85	4.53	0.60	2.72	0.00	9.50	1.40	876.292	837.000	58.419
838	25.43	30.81	25.90	19.01	5.46	0.00	30.29	23.58	14.87	0.00	0.00	0.00	18.56	0.00	24.65	16.07	32.72	26.43	1131.765	838.000	75.451
839	3.24	1.58	0.00	0.00	3.18	5.55	4.81	0.00	0.00	1.32	7.71	0.00	4.42	0.00	0.00	14.16	0.00	13.08	898.035	839.000	74.836
840	3.92	0.00	0.80	0.00	0.41	9.09	0.22	3.81	2.00	4.03	3.73	0.00	1.12	2.26	3.41	0.00	0.22	0.82	875.856	840.000	58.390
841	22.63	25.05	1.12	0.00	3.14	0.00	6.53	3.72	0.00	11.40	22.10	0.00	21.16	22.18	21.13	6.84	7.14	25.19	1040.320	841.000	69.355
842	1.20	5.30	2.16	3.18	0.30	3.52	3.06	0.41	0.72	0.85	1.84	0.30	0.45	1.12	1.10	0.00	0.45	1.04	869.011	842.000	45.737
843	3.49	0.00	0.00	0.00	3.98	1.22	6.94	4.21	5.83	0.00	0.00	3.26	4.52	17.11	0.00	0.00	0.00	2.70	896.261	843.000	74.688
844	1.84	1.51	1.60	2.13	4.22	4.90	0.72	12.83	3.93	4.37	6.59	9.24	5.33	3.35	0.00	2.64	0.28	8.81	918.300	844.000	48.332

Figure 144: Spatial Cognition Study: Second Series, Phase 1 Landmark Placement Results (Page 2 of 2)

Subject	Group	S Total	MV Total	Average Landmark Offset Error (50th's of an inch)	Recognition Errors (out of 30)
845	modified top-down	48.54	25.69	5.29	10
846	modified top-down	33.54	40.28	6.368	6
847	control	36.58	57.64	9.774	4
848	modified top-down	31.89	52.78	1.857	0
849	control	62.19	50	1.497	6
850	modified top-down	77.2	56.25	2.033	3
851	control	57.32	50	7.481	7
852	modified top-down	39.45	-11.11	7.874	8
853	control	50.18	83.33	1.666	7
854	control	37.57	33.33	5.189	10
855	modified top-down	49.79	67.36	6.408	3
856	modified top-down	48.04	43.06	3.363	3
857	control	37.78	60.42	5.325	8
858	modified top-down	61.37	77.08	2.677	4
859	modified top-down	3.68	40.97	11.163	4
860	modified top-down	32.81	31.94	0.965	0
861	control	45.36	37.5	1.104	4
862	control	80.04	76.39	0.861	1
863	modified top-down	29.88	41.67	6.958	9
864	control	43.04	64.58	9.967	4
865	modified top-down	47.93	86.81	1.866	9
866	control	15.07	36.81	12.172	4
867	modified top-down	49.29	64.93	4.441	10
868	control	27.81	45.83	14.796	6
869	modified top-down	28.93	79.86	2.272	9
872	modified top-down	51.29	41.67	0.925	6
873	control	38.29	44.79	13.915	7
879	modified top-down	26.7	17.36	5.418	1
880	control	44.18	46.88	6.464	8

Figure 145: Spatial Cognition Study: Second Series, Phase 2 Data Summary

Second Series Spatial Rotation Scores
Phase 2
from: EKSTROM, R., FRENCH, J., HARMAN, H., and DERMEN, D., Manual for Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service, NR 150 329, 1976.

Participant	S1 (Part 1, 160 questions, 2D rotations)				S2 (Part 2, 42 questions, 3D rotations)				S Total
Number	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	%
845	160	29	102	63.75	160	14	14	33.33	48.542
846	60	3	54	33.75	142	5	14	33.33	33.542
847	98	0	98	61.25	137	7	5	11.9	36.577
848	85	1	83	51.88	133	5	5	11.9	31.89
849	125	3	119	74.38	149	5	21	50	62.188
850	152	2	148	92.5	160	8	26	61.9	77.202
851	106	7	92	57.5	154	6	24	57.14	57.321
852	117	3	111	69.38	154	16	4	9.524	39.449
853	100	4	92	57.5	146	5	18	42.86	50.179
854	113	4	105	65.63	160	19	4	9.524	37.574
855	110	2	106	66.25	156	12	14	33.33	49.792
856	114	3	108	67.5	142	6	12	28.57	48.036
857	85	3	79	49.38	149	10	11	26.19	37.783
858	132	4	124	77.5	155	9	19	45.24	61.369
859	53	13	27	16.88	148	17	-4	-9.52	3.6756
860	109	2	105	65.63	148	15	0	0	32.813
861	104	8	88	55	149	8	15	35.71	45.357
862	123	2	119	74.38	158	2	36	85.71	80.045
863	90	1	88	55	160	20	2	4.762	29.881
864	98	3	92	57.5	136	3	12	28.57	43.036
865	83	1	81	50.63	145	4	19	45.24	47.932
866	73	20	33	20.63	152	15	4	9.524	15.074
867	118	3	112	70	140	5	12	28.57	49.286
868	95	3	89	55.63	140	11	0	0	27.813
869	118	7	104	65	155	20	-3	-7.14	28.929
872	109	1	107	66.88	139	3	15	35.71	51.295
873	105	16	73	45.63	143	6	13	30.95	38.289
879	82	4	74	46.25	141	10	3	7.143	26.696
880	87	9	69	43.13	143	3	19	45.24	44.182

Figure 146: Spatial Cognition Study: Second Series, Phase 2 Spatial Rotation Test Results

Second Series Visual Memory Scores
Phase 1
from: EKSTROM, R., FRENCH, J., HARMAN, H., and DERMEN, D., Manual for Kit of Factor-Referenced Cognitive Tests. Princeton, NJ: Educational Testing Service, NR 150 329, 1976.

Participant	MV1 (Part 1, 32 questions, Shape Memory)				MV2 (Part 2, 24 questions, Building Memory)				MV3 (Part 3, 24 questions, Map Memory)				MV Total
Number	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	# Answered	# Incorrect	Score	%	%
801	32	2	28	87.50	24	0	24	100.00	22	0	20	83.33	90.28
802	32	4	24	75.00	11	0	-2	-8.33	20	0	16	66.67	44.44
803	25	5	15	46.88	18	3	3	12.50	23	3	17	70.83	43.40
804	32	4	24	75.00	15	0	6	25.00	19	0	14	58.33	52.78
805	32	7	18	56.25	22	0	20	83.33	23	0	22	91.67	77.08
806	32	4	24	75.00	15	0	6	25.00	19	0	14	58.33	52.78
807	32	9	14	43.75	18	2	6	25.00	22	0	20	83.33	50.69
808	32	4	24	75.00	18	0	12	50.00	16	0	8	33.33	52.78
809	32	7	18	56.25	15	1	5	20.83	24	0	24	100.00	59.03
810	32	3	26	81.25	20	0	15	62.50	21	0	18	75.00	72.92
811	30	4	22	68.75	17	0	9	37.50	23	0	21	87.50	64.58
812	31	10	11	34.38	8	0	-8	-33.33	14	0	4	16.67	5.90
813	32	5	22	68.75	20	0	16	66.67	21	0	18	75.00	70.14
814	31	5	21	65.63	18	0	12	50.00	21	3	15	62.50	59.38
815	32	6	20	62.50	14	0	4	16.67	21	0	18	75.00	51.39
816	32	5	22	68.75	15	0	6	25.00	22	0	19	79.17	57.64
817	31	0	31	96.88	13	0	2	8.33	22	0	16	66.67	57.29
818	32	6	20	62.50	13	0	2	8.33	23	7	9	37.50	36.11
819	32	9	14	43.75	14	2	0	0.00	20	0	16	66.67	36.81
820	32	4	24	75.00	14	0	4	16.67	18	0	12	50.00	47.22
821	32	11	10	31.25	11	0	-3	-12.50	15	0	6	25.00	14.58
822	32	4	24	75.00	18	0	12	50.00	23	0	21	87.50	70.83
823	32	5	22	68.75	19	0	14	58.33	24	1	23	95.83	74.31
824	32	9	14	43.75	17	0	10	41.67	21	0	17	70.83	52.08
825	32	0	32	100.00	11	0	-2	-8.33	17	0	10	41.67	44.44
826	31	4	23	71.88	21	0	18	75.00	23	0	22	91.67	79.51
827	32	10	12	37.50	8	1	-11	-45.83	15	0	6	25.00	5.56
828	32	5	22	68.75	15	0	6	25.00	20	0	16	66.67	53.47
829	32	21	-10	-31.25	4	0	-16	-66.67	15	0	6	25.00	-24.31
830	32	9	14	43.75	22	3	13	54.17	18	0	12	50.00	49.31
831	32	2	28	87.50	22	0	20	83.33	22	0	20	83.33	84.72
832	31	6	19	59.38	16	0	8	33.33	20	0	16	66.67	53.13
833	32	4	24	75.00	16	0	8	33.33	23	0	22	91.67	66.67
834	32	5	22	68.75	20	0	16	66.67	18	0	12	50.00	61.81
835	32	7	18	56.25	14	0	4	16.67	22	0	20	83.33	52.08
836	32	12	8	25.00	18	0	12	50.00	21	0	18	75.00	50.00
837	32	0	32	100.00	24	0	24	100.00	23	0	22	91.67	97.22
838	32	9	14	43.75	20	0	16	66.67	21	0	17	70.83	60.42
839	32	4	24	75.00	18	0	12	50.00	21	0	18	75.00	66.67
840	32	8	16	50.00	14	1	3	12.50	20	0	16	66.67	43.06
841	32	16	0	0.00	19	0	14	58.33	14	0	4	16.67	25.00
842	32	6	20	62.50	18	2	9	37.50	21	0	18	75.00	58.33
843	32	4	24	75.00	19	0	14	58.33	20	0	16	66.67	66.67
844	32	2	28	87.50	19	0	14	58.33	17	0	10	41.67	62.50

Figure 147: Spatial Cognition Study: Second Series, Phase 2 Visual Memory Test Results

	1			3			4			5		
Subject	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	21.3	21.7	1	27.9	17.7	1	30	20.2	1	25.4	21.7
845	1	29.2	21.5	1	24.9	18	0			0		
846	1	22.1	22.1	0			1	17.1	16	1	25.2	22.5
847	1	22.4	25.7	1	19.9	19.9	1	38.7	26	1	22.5	22.3
848	1	22.7	22.1	1	26.4	18	1	31	21.6	1	25.4	23.6
849	1	22.9	21.8	1	29.9	18	1	29.8	19.3	0		
850	1	23.9	21.9	1	25.3	17.5	1	28.9	13.3	0		
851	1	28.2	21.5	1	22.3	15.2	0			0		
852	1	25	16.7	1	24.4	11.7	1	33.3	14.7	0		
853	1	22.5	22	1	29.9	18	1	29.6	20.9	1	25.8	22.8
854	1	22.5	21.9	1	11.8	18.8	1	30	20	1	25.5	23.7
855	1	29.6	18.2	1	22.7	18.4	1	30.3	13.5	1	25.8	21.9
856	1	28.8	21.3	1	29.4	17.4	1	29.8	19.8	1	25.1	21.7
857	1	27	17.9	1	25.2	11.3	1	33.2	13.9	0		
858	1	20.4	18.3	1	24.9	17.8	1	29.7	23	1	19.9	20.9
859	1	40.2	11.7	1	16.3	19	1	40.5	17.3	1	37	7.8
860	1	22.1	21.9	1	26.9	17.9	1	29.8	20	1	25.2	21.8
861	1	22.7	21.7	1	27.6	17.8	1	29.8	22.3	0		
862	1	23	22	1	26.8	17.9	1	29.8	20.1	1	25.7	22.7
863	1	15.5	22	1	29.6	27.2	1	31.1	21.6	0		
864	1	13.7	20.8	1	15.7	18.3	1	12.5	22.4	0		
865	1	23.8	22.1	1	24.3	17.8	0			0		
866	1	30.3	18.3	1	17.3	18.1	1	33.2	14.7	1	37.9	17.4
867	1	22.9	21.9	1	29.3	17.7	0			0		
868	1	25	9.4	1	4.7	7.8	1	8.4	4.9	0		
869	1	24.8	21.6	1	29.1	21.2	1	29.8	20.7	1	25.7	23.4
872	1	22.3	21.8	1	27.9	18	1	29.7	20.4	1	25.4	22
873	1	0.9	12.7	1	40.9	4.4	0			1	32.1	20.2
879	1	29.6	23.9	1	19.2	15.5	1	13.2	21.5	1	22.5	21.9
880	1	25.6	23.7	1	21.2	17.9	1	30.4	20.2	0		

	7			8			10			12			15		
Subject	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	24.9	17.9	1	17.9	15.9	1	14.3	20.7	1	29.1	21.8	1	33.1	16.3
845	1	25.4	22	1	39.6	14.9	1	18.6	21.3	0			0		
846	1	29.7	20.7	1	18.8	13.9	1	13.1	21.2	1	21.4	18	1	21.8	15.5
847	1	23.9	18.6	1	18.7	21	0			0			1	12.7	11.1
848	1	28.3	20.9	1	18.1	15.6	1	16.9	21.1	1	29.8	22.6	1	34.2	15.3
849	1	28.1	19.2	1	17.9	15.9	1	16.6	21	1	29.8	21.2	1	33.7	16.1
850	1	25.4	20.9	1	17.2	15.8	1	14.3	20.9	1	24.2	21.1	1	33.5	15.6
851	1	25.2	20.4	1	18.2	15.1	1	17	18.2	1	27.5	16.4	1	13.3	21.1
852	1	29.7	10.5	0			0			1	33.8	8.4	0		
853	0			1	17.1	16.3	0			1	31.5	21.5	1	33.4	14.6
854	0			0			1	16	20.9	1	28.4	20.5	1	32.8	16.5
855	1	26	17.2	1	18.7	21.3	1	14.5	21.2	1	29.3	11.6	1	26.6	19.9
856	1	16.4	21.2	1	29.5	14.6	1	18.4	20.5	1	29.7	20.4	1	33.2	16.3
857	0			1	17.6	15.5	1	16.8	20.9	1	33.3	16.7	0		
858	0			1	17.9	16.1	1	14.3	21.2	1	29.7	18.9	1	33.3	11.2
859	0			1	9.8	25.6	1	36.9	20.9	0			1	29.8	21.7
860	1	25	17.9	1	16.7	17.6	1	15.8	21	1	29.6	17.6	1	33.1	14.9
861	0			1	17	16.6	1	15.5	21	1	29.8	22.3	1	33.5	17.4
862	1	25.6	18	1	17.3	16.3	1	15.6	20.8	1	29.5	22.1	1	33.5	14.9
863	1	23.2	27	1	21.8	12.2	0			1	18.9	27	0		
864	1	17.8	15.4	1	24.5	18.6	1	21.6	16	1	16.9	18.7	1	26.5	21.2
865	1	26.9	20.6	0			1	16.8	21.2	1	29.5	21.4	1	33.8	16.9
866	1	35	7.7	1	11.5	23.2	1	20	25.5	1	36.7	7.5	1	19.3	11.7
867	1	25.3	17.9	0			0			1	24.9	26.5	0		
868	1	11.5	2.2	1	27.2	9.1	1	11.7	15.8	1	21	11.9	1	23.9	14
869	0			1	19.4	15	0			1	29.2	19.6	1	29.9	16.4
872	0			1	17.5	16.2	1	14.3	21	1	29.3	21.5	1	33.3	12.5
873	1	33.6	3.5	1	41.7	9.7	1	19.1	9.6	1	29.2	22	1	40.1	11.9
879	1	25.8	21.5	1	15.2	17.4	1	17.5	19.2	1	29.6	20.6	1	33.8	20.2
880	1	28.5	25.6	1	15.2	24.9	1	18.7	20.7	0			1	23.9	12.9

	16			17			19			20			21		
Subject	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y
Key	1	14.3	20.7	1	21.7	16.2	1	33.2	201	1	33.1	11.8	1	30.1	8.9
845	0			1	21.4	16.1	0			1	36.8	21.3	0		
846	0			1	23.5	18.1	0			0			1	29.5	19.2
847	1	14.7	21.7	1	7.4	15.9	1	17.2	237	0			0		
848	1	16.8	18.7	1	23.7	15.6	1	34.5	195	1	34.7	10.8	1	33.1	8.5
849	0			1	23.2	16.1	0			0			0		
850	1	15.4	19.1	1	24.3	15.9	1	33.4	196	0			1	33	8.6
851	1	16.8	21.4	1	19.8	15.8	0			1	27.1	19.4	1	21.2	11
852	1	29.3	15.6	1	29.1	19.5	0			1	40.3	14	0		
853	0			0			1	33.4	186	1	33.2	10.5	0		
854	0			0			0			0			0		
855	1	13.4	22.9	1	17.8	17	0			1	20.5	15.4	0		
856	1	17.7	20.1	1	17.7	16.1	1	33.1	201	1	30.4	8.7	1	24.5	9.5
857	0			1	20.8	15.1	0			0			1	28.6	8.8
858	1	14.5	20.2	1	25.2	9.1	1	29.8	17.7	0			1	29.7	8.6
859	1	29.9	13.3	0			0			1	33.5	10.4	1	30.2	8.3
860	1	13.9	20.4	1	21.5	15.9	1	33.1	203	1	33.2	11.6	1	29.4	8.6
861	1	14.1	20.2	1	21.9	16	1	33.5	207	0			1	33.2	8
862	0			1	20.8	16	1	33.4	195	1	33.4	11	1	29.8	9
863	0			0			0			0			0		
864	1	23.2	14.3	1	20.1	15.8	0			1	15.5	25.4	1	26.2	19.3
865	0			1	20.2	15.5	0			0			0		
866	1	33.4	26.7	1	33.2	11.7	1	44.6	104	0			0		
867	0			1	21.8	15.9	0			0			0		
868	1	9.3	14.4	1	7	10.1	0			0			0		
869	0			1	22	15.8	0			0			0		
872	1	32.9	8.5	1	20.8	16.1	0			0			0		
873	1	9	18.8	1	42.5	20.2	1	20.2	3.8	1	13.1	15.6	0		
879	1	12.4	22.6	1	25.2	9.3	1	33.7	22	1	33.4	11.8	1	23	9.4
880	1	30.8	26.1	0			1	22	152	0			0		

	22			23			24			26			28			30			Total
Subject	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y	r	x	y	
Key	1	29.9	17.5	1	33.2	20.1	1	29.9	13.3	1	24.3	17.8	1	30	20.2	1	33	9.4	20
845	1	29.6	17.3	0			1	29.6	14.1	1	24.5	15.8	0			1	29.7	8.9	11
846	1	16.7	18.8	0			1	19.7	23.9	1	24.4	19	0			1	30.3	8.7	14
847	1	20.7	25.7	1	24.3	23.5	1	18.9	25.9	1	26.1	22	1	20.7	22.2	1	17.2	21.2	16
848	1	30	18.3	1	34.9	17.8	1	30.7	12.3	1	25.5	16.6	1	32.7	20.8	1	35.5	8.6	20
849	1	29.9	17.9	1	33.6	15.4	1	29.7	14.4	1	24.7	17.3	0			1	33.5	8.9	14
850	1	29.7	16.7	1	33.3	18.3	1	32.9	12.4	0			1	30.3	20.3	1	33	9.9	17
851	1	25.1	17	1	29.7	19.7	1	19	23.4	0			0			1	18.7	26.3	15
852	1	39.8	10.6	0			0			0			1	23.1	14.1	1	40.1	9.1	11
853	1	32.5	21.6	0			0			1	26	16.5	1	29.8	19.8	1	32.8	8.3	13
854	1	16.2	18.7	0			1	30.4	14.9	1	11.2	20.4	0			0			10
855	1	24.2	9.9	1	21.9	12.5	1	22.4	21.8	1	17	23.1	1	30.4	22.2	0			17
856	1	26.9	19.4	0			0			1	28.6	15.8	1	31.7	20.7	1	33.3	9.5	18
857	1	33.4	15.5	1	40.2	14.2	1	33.4	9.6	0			1	13.8	20.8	1	33.3	8.1	13
858	1	28.3	18	0			0			1	24.4	16.2	1	28.6	21.5	1	32.8	8	16
859	1	21.3	12	0			1	33.8	18.9	1	40.3	25.4	1	40.4	20.3	1	33.8	26	15
860	1	29.5	18.7	1	33.1	19	1	29.8	13.9	1	24.6	16.9	1	31.2	20.2	1	33.1	8.5	20
861	1	29.3	17.9	1	33.5	19.2	1	29.8	13.9	1	24.7	16.9	0			1	34.4	8	16
862	1	29.8	17.3	1	33.3	18.4	1	29.8	14.4	1	24.6	17	1	30.4	20	1	33.1	8.9	19
863	1	26.3	21.5	0			0			0			0			0			7
864	1	17.8	19.3	0			1	20.4	11.9	1	17.1	22.3	0			1	29.5	21.4	16
865	1	29.1	16.5	0			1	29.6	11.2	1	24.6	16.4	0			1	33.5	9.3	11
866	1	29	18.2	1	15.4	18.2	0			0			1	13	29.1	1	12	26.6	16
867	1	29.3	16.7	1	33.3	18.5	1	29.2	15.3	1	24.5	17	0			1	9.5	26.1	10
868	1	9.7	4.8	1	26.7	11.3	0			1	9.3	1.3	0			1	23.4	8.9	14
869	1	30.1	21.5	0			1	29.8	17.5	0			1	31.1	20.7	1	32.8	8.7	12
872	1	29.9	17.4	1	33.3	17.7	1	29.9	15	0			0			1	32.9	8.5	14
873	1	37.7	8.6	1	13	10.6	1	24.5	10.3	1	11.5	4.6	0			1	37.7	6.2	17
879	1	23.8	14.2	1	33.4	16.8	1	29.8	15.9	1	20.9	12.2	1	26.8	12.4	1	22.6	7.9	20
880	1	24.5	16.9	0			0			1	24.3	20.7	0			1	20.2	12	12

Figure 148: Spatial Cognition Study: Second Series, Phase 2 Landmark Placement Results (Page 1 of 2)

Subject	1	3	4	5	7	8	10	12	15	17	19	20	21	22	23	24	26	28	30	Total	Maximum	Average
Key	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.000	0.000
845	7.90	3.01	0.00	0.00	4.13	21.72	4.34	0.00	0.00	0.32	0.00	10.20	0.00	0.36	0.00	0.85	2.01	0.00	3.34	58.186	21.723	5.290
846	0.89	0.00	13.57	0.82	5.56	2.19	1.30	8.59	11.33	2.62	0.00	0.00	10.32	13.26	0.00	14.71	1.20	0.00	2.79	89.153	14.711	6.368
847	4.15	8.30	10.46	2.96	1.22	5.16	0.00	0.00	21.05	14.30	16.40	0.00	0.00	12.32	9.53	16.73	4.57	9.51	19.72	156.381	21.052	9.774
848	1.46	1.53	1.72	1.90	4.53	0.36	2.63	1.06	1.49	2.09	1.43	1.89	3.03	0.81	2.86	1.28	1.70	2.77	2.62	37.149	4.534	1.857
849	1.60	2.02	0.92	0.00	3.45	0.00	2.32	0.92	0.63	1.50	0.00	0.00	0.00	0.40	4.72	1.12	0.64	0.00	0.71	20.961	4.717	1.497
850	2.61	2.61	6.99	0.00	3.04	0.71	0.20	4.95	0.81	2.62	0.54	0.00	2.92	0.82	1.80	3.13	0.00	0.32	0.50	34.554	6.987	2.033
851	6.90	6.13	0.00	0.00	2.52	0.85	3.68	5.63	20.37	1.94	0.00	9.68	9.14	4.83	3.52	14.86	0.00	0.00	22.14	112.209	22.138	7.481
852	6.22	6.95	6.41	0.00	8.82	0.00	0.00	14.20	0.00	8.10	0.00	7.53	0.00	12.07	0.00	0.00	0.00	9.21	7.11	86.616	14.200	7.874
853	1.24	2.02	0.81	1.17	0.00	0.89	0.00	2.42	1.73	0.00	1.51	1.30	0.00	4.85	0.00	0.00	2.14	0.45	1.12	21.653	4.855	1.666
854	1.22	16.14	0.20	2.00	0.00	0.00	1.71	1.48	0.36	0.00	0.00	0.00	0.00	13.75	0.00	1.68	13.36	0.00	0.00	51.890	16.138	5.189
855	9.01	5.25	6.71	0.45	1.30	5.46	0.54	10.20	7.43	3.98	0.00	13.10	0.00	9.50	13.62	11.34	9.02	2.04	0.00	108.942	13.618	6.408
856	7.51	1.53	0.45	0.30	9.12	11.67	4.10	1.52	0.10	4.00	0.10	4.11	5.63	3.55	0.00	0.00	4.74	1.77	0.32	60.532	11.673	3.363
857	6.85	6.95	7.07	0.00	0.00	0.50	2.51	6.61	0.00	1.42	0.00	0.00	1.50	4.03	9.15	5.09	0.00	16.21	1.33	69.227	16.211	5.325
858	3.52	3.00	2.82	5.56	0.00	0.20	0.50	2.96	5.10	7.92	4.16	0.00	0.50	1.68	0.00	0.00	1.60	1.91	1.41	42.840	7.916	2.677
859	21.38	11.67	10.89	18.10	0.00	12.64	22.60	0.00	6.33	0.00	0.00	1.46	0.61	10.21	0.00	6.82	17.71	10.40	16.62	167.449	22.601	11.163
860	0.82	1.02	0.28	0.22	0.10	2.08	1.53	4.23	1.40	0.36	0.22	0.22	0.76	1.26	1.10	0.61	0.95	1.20	0.91	19.292	4.230	0.965
861	1.40	0.32	2.11	0.00	0.00	1.14	1.24	0.86	1.17	0.28	0.67	0.00	3.23	0.72	0.95	0.61	0.98	0.00	1.98	17.658	3.228	1.104
862	1.73	1.12	0.22	1.04	0.71	0.72	1.30	0.50	1.46	0.92	0.63	0.85	0.32	0.22	1.70	1.10	0.85	0.45	0.51	16.368	1.726	0.861
863	5.81	9.65	1.78	0.00	9.26	5.38	0.00	11.45	0.00	0.00	0.00	0.00	0.00	5.38	0.00	0.00	0.00	0.00	0.00	48.703	11.449	6.958
864	7.65	12.21	17.64	0.00	7.53	7.13	8.68	12.59	8.22	1.65	0.00	22.24	11.11	12.23	0.00	9.60	8.49	0.00	12.50	159.479	22.242	9.967
865	2.53	3.60	0.00	0.00	3.36	0.00	2.55	0.57	0.92	1.66	0.00	0.00	0.00	1.28	0.00	2.12	1.43	0.00	0.51	20.529	3.601	1.866
866	9.62	10.61	6.36	13.22	14.35	9.71	7.45	16.19	14.55	12.35	14.97	0.00	0.00	1.14	17.90	0.00	0.00	19.19	27.14	194.758	27.145	12.172
867	1.61	1.40	0.00	0.00	0.40	0.00	0.00	6.30	0.00	0.32	0.00	0.00	0.00	1.00	1.60	2.12	0.82	0.00	28.83	44.408	28.829	4.441
868	12.84	25.22	26.47	0.00	20.64	11.52	5.55	12.79	9.48	15.92	0.00	0.00	0.00	23.86	10.94	0.00	22.30	0.00	9.61	207.150	26.470	14.796
869	3.50	3.70	0.54	1.73	0.00	1.75	0.00	2.20	3.20	0.50	0.00	0.00	0.00	4.00	0.00	4.20	0.00	1.21	0.73	27.262	4.201	2.272
872	1.00	0.30	0.36	0.30	0.00	0.50	0.30	0.36	3.81	0.91	0.00	0.00	0.00	0.10	2.40	1.70	0.00	0.00	0.91	12.945	3.805	0.925
873	22.30	18.60	0.00	6.87	16.82	24.59	12.09	0.22	8.27	21.18	20.85	20.36	0.00	11.83	22.32	6.18	18.39	0.00	5.69	236.560	24.594	13.915
879	8.59	8.97	16.85	2.91	3.71	3.09	3.53	1.30	3.96	7.74	1.96	0.30	7.12	6.94	3.31	2.60	6.55	8.43	10.51	108.366	16.850	5.418
880	4.74	6.70	0.40	0.00	8.50	9.40	4.40	0.00	9.81	0.00	12.22	0.00	0.00	5.43	0.00	0.00	2.90	0.00	13.06	77.569	13.061	6.464

Figure 149: Spatial Cognition Study: Second Series, Phase 2 Landmark Placement Results (Page 2 of 2)

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